REVISTA PORTUGUESA DE QUÍMICA

RPTQAT 16(4) 195-268 (1974)

Rev. Port. Quím., Vol. 16, N.º 4
Pp. 195-268 — Lisboa, 1974

REVISTA PORTUGUESA DE QUÍMICA

Propriedade e edição da
SOCIEDADE PORTUGUESA DE QUÍMICA
em continuação da
REVISTA DE QUÍMICA PURA E APLICADA
fundada em 1905 por
Ferreira da Silva.
Subsidiada pelo
INSTITUTO NACIONAL DE INVESTIGAÇÃO CIENTÍFICA

Redacção e administração	Instituto Superior Técnico — Lisboa-1 (Tel. 56 29 13)
Gravuras, composição e impressão	Gráfica Brás Monteiro, Lda. — Lisboa
Capa e arranjo gráfico	Luís Filipe de Abreu

Publicação trimestral. Número avulso: 150$00. Assinatura (quatro números): Portugal, Brasil e Espanha: 500$00
outros países: U.S. $18.00

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I. WILLIAMS (2)

A. B. HEDLEY

Dept. of Chemical Engineering and Fuel Technology
University of Sheffield — England

THE BEHAVIOUR OF DROPLETS WITHIN TURBULENT PIPE FLOW (1)

Several approaches to the calculation of the rate of deposition of particles from turbulent pipe flow onto boundary walls, are discussed. The need to consider the relationship between the eddy diffusivity of mass and momentum was indicated and quantified by experiment. The flow was assumed to be two-dimensional and was characterized by measurements of: the mean and r.m.s. fluctuating velocities respectively in the radial and axial directions as well as the fluid shear stress distribution. From the latter, the eddy diffusivity of the fluid was estimated. The measurements were made at Re No $= 1.27 \times 10^5$ and 2.64×10^4 *respectively at a pipe wall temperature of 294.0°K. Droplets of di-2-ethyl hexyl sebacate in the size range 0.54 — — 2.6 μm dia. were injected into the flow and their deposition velocities were measured, showing an increase with drop size and Re No respectively.*

The prediction of the rate of deposition of particles from a turbulent fluid on to boundary surfaces has many important applications. Examples include deposition in atomic reactors, spray dryers, particle sampling lines and in any flow system where suspended particles are transported from a generating source to the place of application.

A straight, smooth walled, cylindrical duct offers the most convenient means for studying the rate of particle deposition in turbulent flow systems. The processes by which particles deposit on a pipe wall include [1], eddy diffusion, gravity settling, thermophoresis, diffusiophoresis, electrostatic effects and inertial effects such as impaction and interception. The parameter K, which describes the deposition rate, has been defined as [2]

$$K = \frac{\text{amount of particulate deposited per cm}^2 \text{ of surface s}^{-1}}{\text{the airborne particulate concentration above the surface}}$$

The approach to the problem has usually been to evolve methods of predicting K for different systems and to correlate the predictions experimentally.

In the following investigations the following assumption was often made. The structure of the turbulent fluid in pipe flow consisted of a laminated boundary layer and a turbulent core. The boundary layer was characterized by three regions [3]:

(i) laminar sublayer, $y^+ < 5$;
(ii) buffer layer, $5 < y^+ < 30$;
(iii) main boundary layer, $y^+ > 30$,

where, y^+ is the dimensionless variable, yu_τ/ν, y is

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(1) Presented at CHEMPOR' 75 held in Lisbon, 7-12 September 1975 at the Calouste Gulbenkian Foundation Center.
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(2) Present address: Shell Research Ltd., Thornton Research Centre, P. O. Box 5, Chester CH1 3SH.

the distance normal to the surface measured outwards, and u_τ is the fluid friction velocity defined as

$$u_\tau = \sqrt{(\tau_0/\rho)}. \tag{1}$$

τ_0 is the tangential shearing stress on the surface over which the fluid flows, ρ is the fluid density, and ν is the fluid kinematic viscosity.

The equation used to describe the rate R of transport of particles from the turbulent core to the wall is

$$R = (D + \varepsilon_p)dC/dy, \tag{2}$$

where D is the molecular diffusivity and ε_p is the particle eddy diffusion coefficient due to the turbulence; C is the concentration of the diffusing substance at a distance y from the surface. The particles were usually assumed to diffuse by eddy diffusion from a constant particle concentration in the turbulence core of the pipe up to, and in some theories, into, the boundary layer. In the diffusion process the eddy diffusivities of the particle and fluid were assumed equal. At the point where the eddy diffusion process was assumed to end, the particle was associated with a free flight velocity v, and a stop distance [3] ds, where $ds = v_f{}'\tau$ and τ is the particle relaxation time. For particles obeying Stokes law of resistance,

$$\tau = \frac{m}{6\pi r_p \eta} = \frac{2^r p^{2\rho} p}{9\eta} \tag{3}$$

where r_p is the particle radius, m the particle mass, ρ_p its density and η is the viscosity of the fluid. The value of v was usually equated to a function of the root-mean-square radial resolute of the fluid fluctuation velocity $v_f{}'$.

FRIEDLANDER and JOHNSON [4] derived deposition velocities on the basis of the above postulate. They assumed that $v = 0.9\, u_\tau$. This figure seemed unreasonably high and according to the fundamental turbulence measurements made by LAUFER [5] this velocity existed at a distance $y^+ = 80$ which was within the turbulent core and not within the boundary layer. Even using such a high initial velocity, the particle stopping distance was often less than the thickness of the laminar sublayer. This led FRIEDLANDER and JOHNSON [4] to use the hypothesis of LIN *et al.* [6] who determined the following empirical expression for ε_f, the fluid eddy diffusivity, within the laminar sublayer:

$$\varepsilon_f/\nu = (y+/14.5)^3 \tag{4}$$

According to this model, eddies from the turbulent core at a distance $y^+ = 80$, penetrated the boundary layer and retained their momentum until they were within a distance S^+, from the wall, where $S^+ = 0.9\tau^+$ and τ^+, the dimensionless particle relaxation time was equal to $\tau u^2{}_\tau/\nu$. A finite eddy diffusivity within the laminar layer was assumed. When S^+ was calculated using the actual values of v' at $y^+ = S^+$, transport coefficients were obtained which were four orders of magnitude lower than those found experimentally by FRIEDLANDER and JOHNSON [4].

DAVIES [7] derived a deposition scheme in which he considered both inertial deposition and deposition by Brownian diffusion. The particle radius was taken as the distance of closest approach to the deposition surface. The main difference between this theory and that mentioned previously for inertial deposition [4] was that Davies calculated his free-flight particle velocity from an analytical expression derived from the measured turbulent velocity data in fully-developed turbulent pipe flow obtained by LAUFER [5]. He determined this velocity at a distance from the wall equal to $(S^+ + a^+)$, where $a^+ = r_p \times U_\tau/\nu$, not as previously [4], in the turbulent core. LAWRENCE and HUANG [8] adapted this theory and obtained solutions valid for a cylindrical coordinate system rather than the rectangular coordinate system used by DAVIES [7]. In all the above work, re-entrainment of particles from the boundary walls was assumed to be absent. Reviews of these theories and of others [9-12] differing little from the above have been given by MONTGOMERY and CORN [13] and SEHMEL [14].

In a more recent theory, LAWRENCE and HUANG [8] considered that the size of the particles relative to the scale of the turbulence was of importance and they defined a relative entrainment factor, as

$$\alpha = ds/1, \tag{5}$$

where 1 is the fluid mixing length [15] at a point within the fluid. If this ratio was greater than unity the concept of a particle stop distance was used; however, if the quantity, α was less than unity then the mixing length was used as a measure of the particle free flight distance. On the basis of work by TCHEN [16] and SOO and TIEN [17] the authors assumed equality of particle and fluid diffusivities but included a specification of the particle root-mean-square turbulent fluctuation velocity, $v_p'^{+}$, with respect to the r.m.s. fluid fluctuation velocity, $v_f'^{+}$, in the form of a non-linear differential equation relating the latter two quantities and the particle relaxation time in the following manner:

$$\frac{dv_p'^{+}}{dy^{+}} = \frac{1}{\tau^{+}}\left(1 + \frac{v_f'^{+}}{v_p'^{+}}\right). \qquad (6)$$

The authors calculated the discrete particle deposition flux for fully-developed turbulent pipe flow. The results deviated widely, as did those in all the previous work reviewed, from the small amount of experimentally obtained aerosol deposition data available from other sources.

ROUHIAINEN and STACHIEWICZ [18] used the concept of frequency response developed by HJELMFELT and MOCKROS [19] to obtain a quantitative evaluation of $\varepsilon_p/\varepsilon_F$. They showed that for 30 μm diam. particles of lycopodium spore, a fourfold increase in Reynolds number Re of the suspending fluid which caused a more than fourfold increase in ε_F, only resulted in a twofold increase in ε_p. A more important result of their work for small particles was their quantitative evaluation of the shear flow induced transverse lift force on a particle in the laminar sublayer. They considered that for a vertical flow system, if the particle radial velocity was sufficient to carry the particle to such a distance from the wall, that the particle velocity in the x coordinate direction was higher than the local stream velocity in this direction, then the lift force was directed towards the wall. For lycopodeum spheres of 2 μm diam. they calculated that for $Re > 1 \times 10^4$, the particle velocity at the edge of the sublayer such that deposition on the wall took place, was three orders of magnitude lower when considering the lift force effect than when a purely inertial mechanism was considered.

SEHMEL [1] examined the effect of removing the assumptions regarding an equality of diffusivity of the particle and fluid and an equality of particle and fluid root-mean-square turbulent fluctuation velocities. He determined what dependence these variables had upon other parameters of the problem in order that theoretical calculations agreed with the experimental data, i.e. he described the combined effect of the two parameters as an «effective eddy diffusion coefficient» and gave empirical correlations for predicting this quantity for various flow conditions. He also made deposition measurements on all surfaces of a duct and introduced a gravitational factor into the correlations.

In the last few years however, it has become possible to look at the dynamics of fluid behaviour at much smaller values of y^{+} than previously and work by RUNSTADLER *et al.* [20], KIM, KLINE and REYNOLDS [21], and GRASS [22] respectively has shown a relatively unknown flow pattern near the wall in turbulent bounded flow.

Turbulence appears to be produced by a regular series of eruptions of low momentum fluid which propagate outwards through a considerable depth of boundary layer dissipating in energy as y^{+} increases. A simultaneous transfer of low momentum fluid occurs towards the wall with the result that a regularly disturbed boundary layer structure is

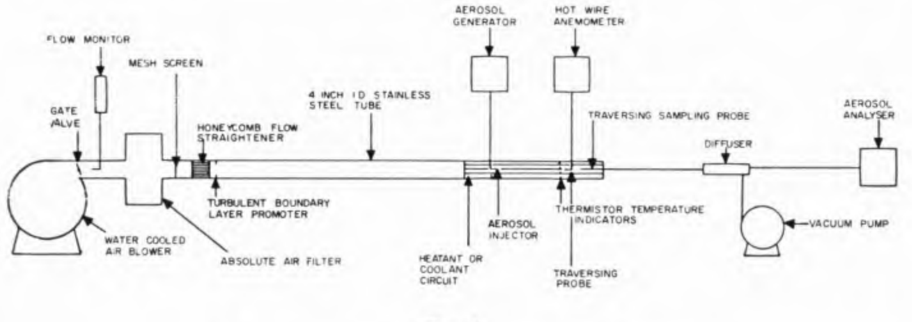

Fig. 1
A diagrammatic view of the experimental system

set up rather than the stratified laminated structure previously assumed in work on turbulent mass transfer. Measurements using hot film anemometry carried out by Eckelman [23] in fully developed channel flow has suggested that the fluid fluctuation velocity approaching the wall is of a similar magnitude to the friction velocity, an assumption made many years previously by Friedlander [4] though for different reasons and previously reported by Reichart [24].

Having reasonably established the transfer of momentum to a bounding wall in turbulent flow a correlation for equivalent mass transfer required that, a relationship between the ratio of the eddy diffusivity of the fluid, ε_F, to the eddy diffusivity of a particle, ε_p, and the flow properties of the fluid, was obtained.

As a first approximation it was assumed that the fluid in fully developed turbulent pipe flow fluctuated in a sinusoidal motion of frequency, f.

If it was assumed that the force, F, acting upon an entrained particle was that given by Stokes expression,

$$F = 6\pi\mu_F r_p Vr \tag{7}$$

where μ_F was the absolute viscosity of the fluid and Vr was the terminal particle velocity, then it was predicted by Rosenschweig [25] that the entrained droplet would vibrate sinusoidally with a velocity amplitude ratio of,

$$\frac{V_{\text{particle}}}{V_{\text{fluid}}} = [1 + (4\pi f r_p{}^2 \rho_p / 9\mu_F)^2]^{-\frac{1}{2}} \tag{8}$$

The above expression was solved for 1 and 5 μm diameter droplets vibrating in turbulent pipe flows of Re $= 1.27 \times 10^5$ and 2.64×10^4 respectively at the corresponding frequencies calculated for our present work, the results are given in Table 1 and show that the deviation of the relationship from unity was theoretically negligible.

It was apparent from the current state of aerosol deposition studies in turbulent flow, that certain aspects of the problem warranted further investigation; these were: (1) more experimental results of particle deposition rates from turbulent pipe flow under closely controlled conditions were needed and (2) the relationship between the particle diffusivity and the fluid diffusivity $\varepsilon_p/\varepsilon_F$ under practical conditions needed clarification.

It was decided to construct a variable flow system in which fully-developed turbulent pipe flow was achieved. An initial investigation was designed to characterize the flow in terms of the mean and fluctuating velocities U, u′, V, v′ in the axial and radial directions respectively, and to allow the determination of the shear stress, $\overline{uv}$ as a function of y and hence the eddy diffusivity of the fluid from the relationship

$$\varepsilon/\upsilon = \frac{\overline{uv}/u_\tau{}^2}{du^+/dy^+} \quad , \tag{9}$$

where

$$\frac{du^+}{dy^+} = \frac{d(U/U_o)}{d(y/a)} \; \frac{U_o\upsilon}{U_\tau a U_\tau} \tag{10}$$

and a is the pipe radius, U is the mean axial velocity at a point, and U_0 is the maximum mainstream velocity at the centre line.

The measurement of the above quantities was carried out using hot-wire anemometry. Non-volatile droplets having a low surface tension of 30 MN m^{-1} were chosen as the disperse phase since in the deposition measurements mass transfer and re-entrainment from the walls respectively would be minimized. By carrying out concentration traverses of the aerosol injected into the turbulent flow, the diffusivity of the particles in the fluid was determined. The measurement of the aerosol concentration was carried out by sampling the aerosol isokinetically and using a multi-channel light-scattering counter which was developed for the purpose [26].

In this experiment the effect of charge was minimized by generating a condensation aerosol, examining it for charge using a charge analyzer and if necessary neutralizing the aerosol using a charge generator designed to produce equal numbers of $^+$ve and $^-$ve ions.

The experimental unit is shown diagrammatically in fig. 1 and consisted of three units, the flow system, the aerodynamic analysis system and the aerosol generation and analysis unit. The duct assembly consisted of a valve regulated blower

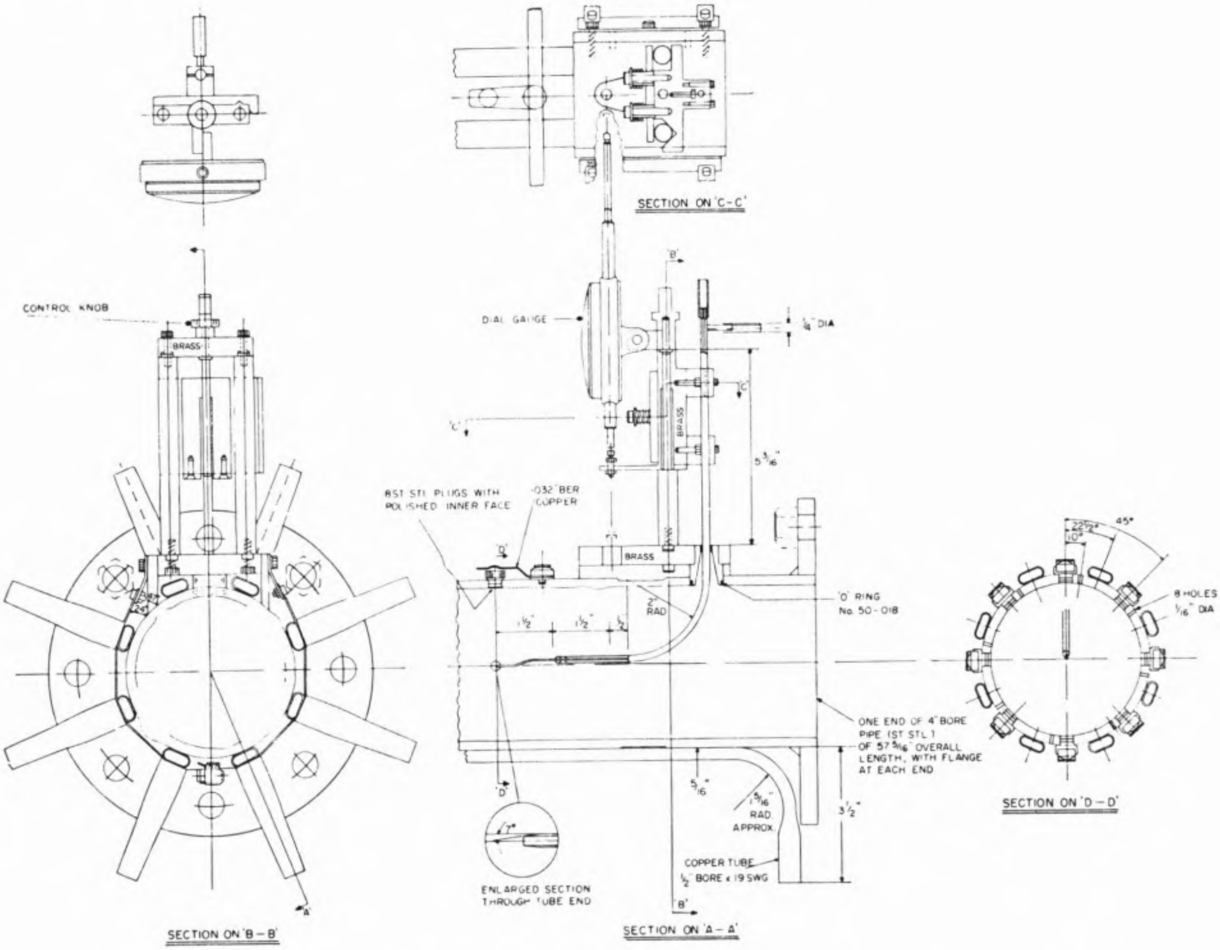

Fig. 2

Test section for turbulent pipe flow rig showing probe traversing mechanism with a pilot static tube in situ

which passed up to 0.4 m^3 s^{-1} of cooled air through an absolute filter unit, a 0.6 cm mesh screen and a 35-cm-long section of paper honeycomb into the first of six interlocking sections of 10.16 cm i.d. 154.2 cm long stainless steel tubes each of which was mirror polished internally. The turbulent boundary layer was instigated by an annular protuberance of 1.5 mm depth in the first section. Each tube was fitted with the facility to accomodate an aerosol injection point in the form of an airfoil wedge section across the duct. The last two sections of the duct acted as test sections and were fitted with 20 equispaced pressure tappings and each section had facilities for fitting a probe scanning unit shown in fig. 2. Around the periphery of the duct at the corresponding axial position to the internal probe tip, eight thermistors recorded the internal wall temperature and eight adjacent, removable plugs were fitted flush with the inside tube wall to act as droplet sample holders which were subsequently examined microscopically. The wall temperature of the last section of the duct was controlled by passing ethylene glycol through eight, 1.27 cm i.d. copper tubes fastened to the outer tube wall. The flow Reynolds number range available with the unit was between 2.64×10^4 and 1.27×10^5 with wall temperatures between 279 and 317 °K.

The second unit in the experiment a DISA hot-wire anemometer type 55D01 was used to determine the aerodynamic characteristics of the fluid flow. These quantities were the fluid shear stress $-\overline{uv}$, where u and v were the instantaneous values of velocity fluctuations in the x or y directions respectively, the mean axial velocities, U and U_0, and the root-mean-square fluctuating velocity components in the axial and radial directions, u′ and v′. In order to determine v′, it was necessary to determine the double correlation coefficient $\overline{uv}/u'v'$. The probes used in the experiment were DISA gold-plated miniature probes, types 55F14, 55F12 and 55F11, to measure the average velocity profiles, the shear stress and the fluctuating root-mean-square velocities respectively. The correlation coefficient was measured at several points during a traverse in the test section, using a DISA cross-wire probe. In the aerodynamic measurements two dimensional duct flow was assumed.

The effect of the fluid temperature variation on the hot-wire results was taken into account by calibrating the probes at several temperatures within the range of interest. A plot of the calibration constants against the temperature was then made. For calibration purposes the DISA calibration wind tunnel was used with a modification. The air was heated or cooled by passing through an automobile radiator at the inlet to the tunnel. Ethylene glycol acted as heatant or coolant and the temperature of the air in the wind tunnel was monitored using a thermistor.

The third part of the experimental apparatus was the aerosol generation, sampling and analysis unit.

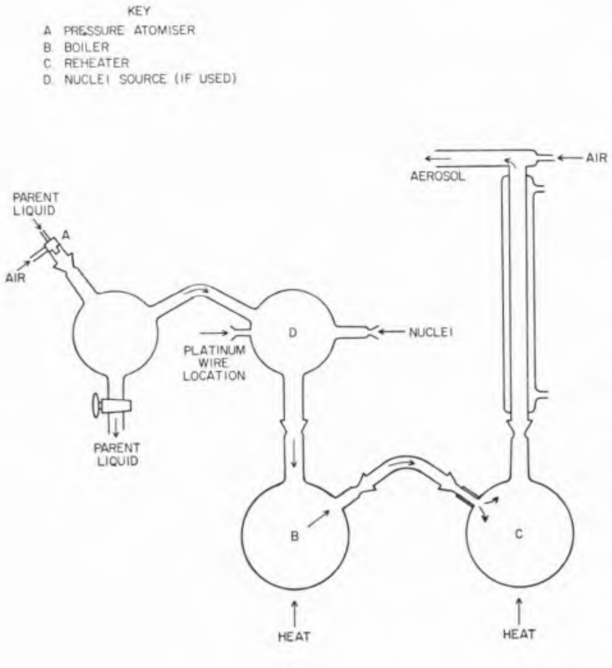

Fig. 3
The aerosol generator

The aerosol was generated from di-2-ethyl hexyl sebacate in a generator shown diagrammatically in fig. 3. This was a condensation generator, a description of which had been given previously [27]. Some modifications to the generator were made for this work. The two most important were the provision of additional flow controllers at the outlet of each gas supply and a more sophisticated temperature control system. The temperature controller incorporated an electronic proportional control circuit with a fine differential control applied. The sensor units were negative temperature coefficient thermistors which were fitted into the boiler and reheater flasks respectively. This unit enabled temperature control within ± 0.5 °C which was necessary for a reproducible aerosol. The use of a condensation generator precluded the formation of charged droplets. That this condition was satisfied was tested by passing the aerosol in a laminar air stream between two plates with a potential of 5 kV between them. The plates were examined for deposited droplets using photomicrography, and if necessary, the aerosol was neutralized by passing through a charge apparatus designed to generate equal number of $^{+}$ve and $^{-}$ve ions, both the charge analyzer and charger were designed after LANGER and RADNICK [28].

Particles were pumped through the sampling probe and then through a conical diffuser, to a sensing system where the particles were classified into ten size-ranges and total counts in each range were indicated digitally.

The anemometer hot-wire data was processed using a statistical approach to the signal analysis developed by DVORAK and SYRED [29].

This method was applied to the two-dimensional system under discussion and necessitated measurements from a straight wire probe in two 90° mutually differing positions. The equations were solved for the mean and fluctuating velocities in the axial and radial directions at a number of points on a traverse across the duct test-section.

The correlation coefficient was measured at several points across the duct using a cross-wire probe. The shear stress component was evaluated from measurements made with a 45°-slant wire probe [30] rotated through 180° by assuming that the heat transfer from the wire depended only upon the flow velocity normal to the wire.

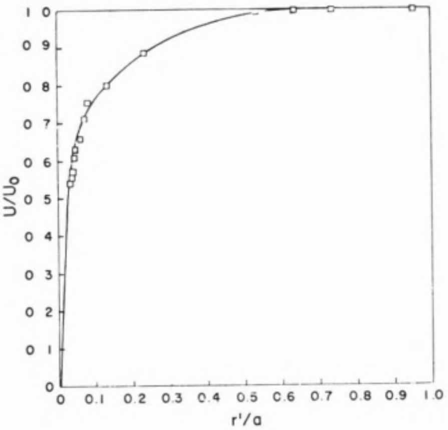

Fig. 4
The fluid velocity profile in turbulent pipe flow at $Re = 2.64 \times 10^4$

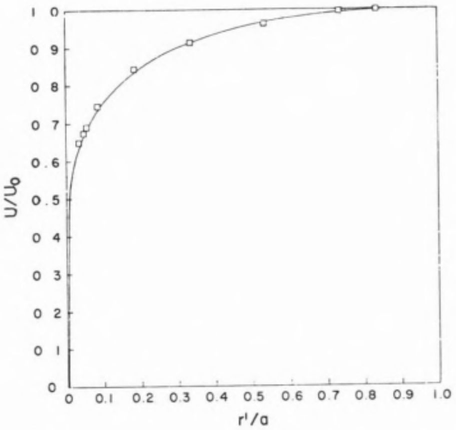

Fig. 5
The fluid velocity profile in turbulent pipe flow at $Re = 1.27 \times 10^5$

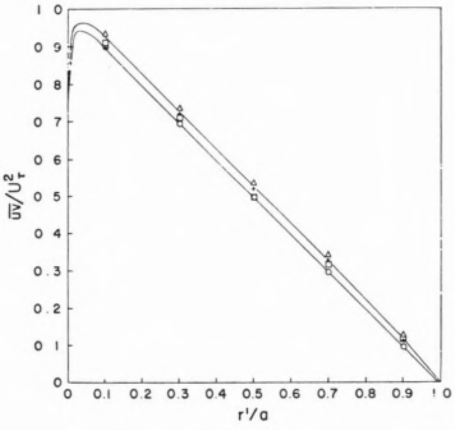

Fig. 6
The shear stress profile of turbulent pipe flow
Curve 1, $Re = 1.27 \times 10^5$; Curve 2, $Re = 2.64 \times 10^4$

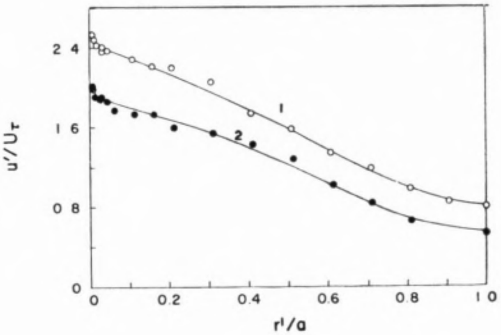

Fig. 7
The distribution of u' within turbulent pipe flow at $Re = 1.27 \times 10^5$ and 2.64×10^4 respectively
Curve 1, represents $u'/U\tau$ at $Re = 1.27 \times 10^5$
Curve 2, represents $u'/U\tau$ at $Re = 2.64 \times 10^4$

In a fully-developed pipe flow the velocity distribution across a pipe is independent of the stream wise position. Under these conditions the pressure drop along a pipe is balanced by the tangential stress, τ_0, where,

$$\tau_0 = a dP/2dx \qquad (11)$$

In this experiment the static pressure tapping along the last two pipe sections enabled a measurement of dP/dx, the pressure drop, to be made and so a direct determination of the tangential wall stress was possible,

Fig. 4 shows the velocity profile across the test section, at $Re = 2.67 \times 10^4$ and fig. 5 shows similar data for $Re = 1.27 \times 10^5$.

A plot of the shear stress, non-dimensionalized with the friction velocity, as a function of r'/a is shown in fig. 6. The curves correspond to Reynolds numbers of 2.67×10^4 (upper curve) and $1.27 \times \times 10^5$ (lower curve).

The distribution of the axial root-mean-square,

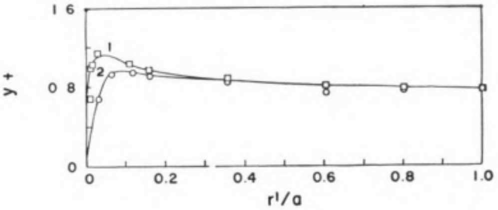

Fig. 8
The distribution of v' within turbulent pipe flow at $R = 1.27 \times 10^5$ and 2.67×10^4 respectively
Curve 1, represents v' at $Re = 1.27 \times 10^5$
Curve 2, represents v' at $Re = 2.64 \times 10^4$

fluctuating, turbulent velocity component u′, non-dimensionalized with U_τ, is shown in fig. 7. The upper curve shows the distribution of a Reynolds number of 1.27×10^5 and the lower curve was determined for a Reynolds number of 2.64×10^4.

The last of the turbulent quantities, the distribution of the radial root-mean-square turbulent fluctuating velocity component, v′, is shown in fig. 8. This quantity was again non-dimensionalized with the friction velocity. The upper curve corresponds to a Reynolds number of 1.27×10^5 and the lower curve to one of 2.64×10^4.

Finally, fig. 9, shows the eddy diffusivity of the fluid in the turbulent pipe flow, non-dimensionalized with the kinematic viscosity of air, plotted against the non-dimensional parameter y^+. The figure shows the results at Reynolds numbers of 1.27×10^5 and 2.64×10^4 and also the theoretical points derived from Ref. 6.

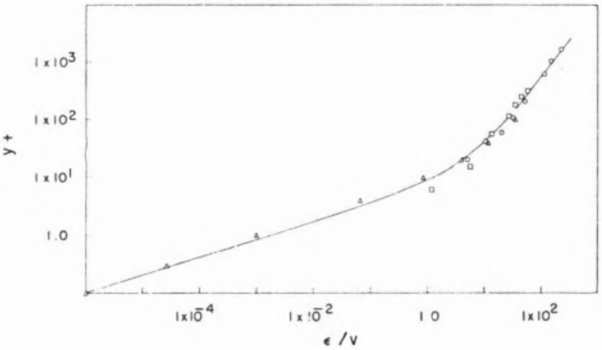

Fig. 9

The fluid eddy diffusivity distribution in turbulent pipe flow. ○, results obtained at Re = 1.27 × 10⁵; □, results obtained at Re = 2.64 × 10⁴; △, theoretically derived results from ref. (7)

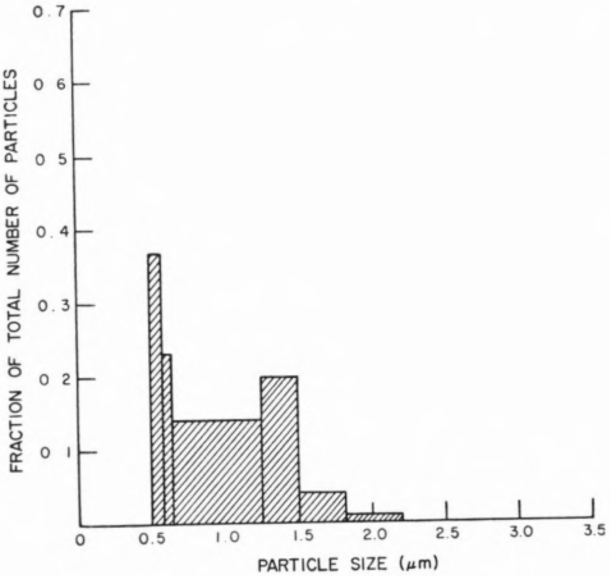

Fig. 10

Aerosol size distribution

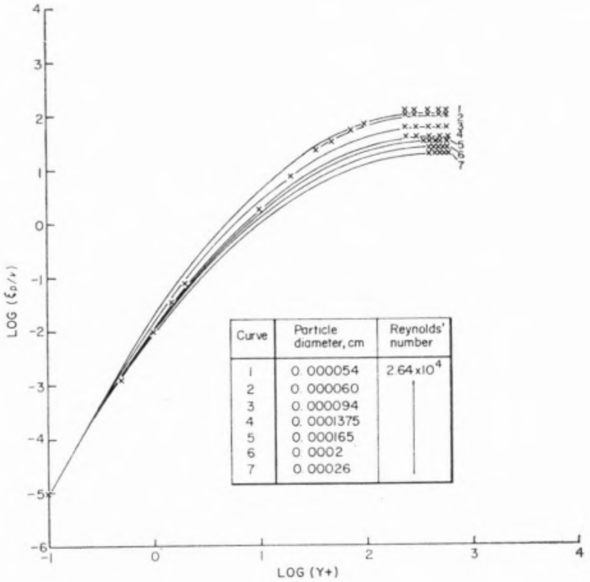

Fig. 11

Relationship between particle diffusivity and the distance from the wall of the tube

With regard to the determination of the fluid dynamic characteristics of the flow in the duct,

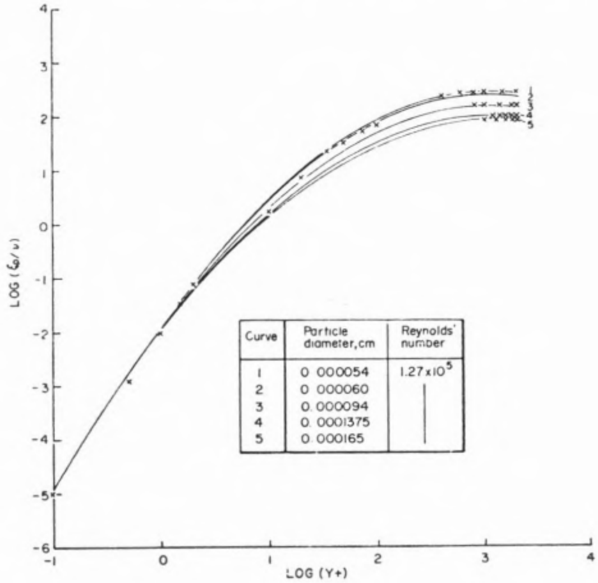

Fig. 12

Relationship between particle diffusivity and the distance from the wall of the tube

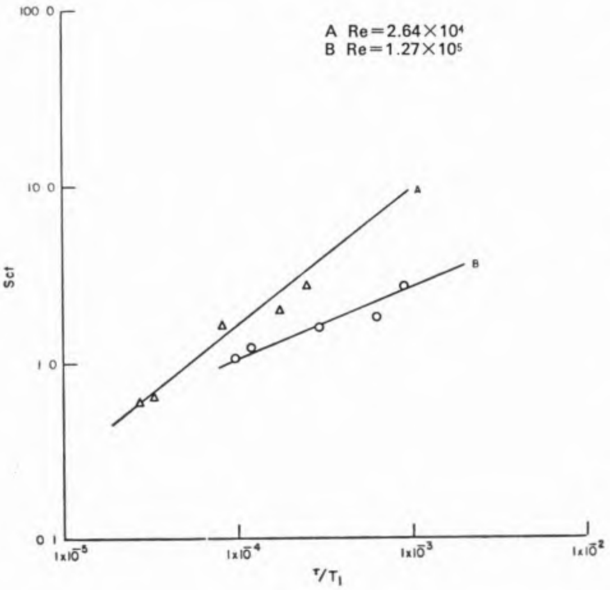

Fig. 13

The relationship between, $\tau/T_1 \dfrac{\textit{the particle relaxation time}}{\textit{fluid macro scale}}$ *and* $\xi f/\xi p$*, Sct No.*

it was necessary to determine how closely the present system approached fully-developed turbulent flow. This was indicated by several features. For both values of Reynolds number, the velocity profiles were typical, flat, turbulent profiles as opposed to the parabolic profile expected from laminar flow. The shear stress profiles shown in fig. 6 showed little dependence on Reynolds number and varied linearly across the duct cross-section.

The turbulent intensities, u'/U_0 were calculated for $r'/a = 0.1$ and 1.0 for Reynolds number of 1.27×10^5 and 2.64×10^4. The intensities were compared with those calculated by LAUFER [5] for Reynolds numbers of 5×10^5 and 5×10^4 and the comparison is shown in Table 2. The similarity of the magnitude of the turbulent intensities in the present system and those measured by LAUFER [5] at higher Reynolds numbers indicated that fully-developed turbulent flow was achieved in our system.

Having established the flow characteristics in our pipe flow system, an aerosol, consisting of droplets of di-2-ethyl hexyl sebacate suspended in air, with a constant size distribution shown in fig. 10, was introduced at the centre line of the duct through a point source injection system. The mass concentration of material leaving the injector was approximately 8×10^{-8} gm cm^{-3}.

The individual particle concentrations were determined at radially displaced locations from the tube centre line to the wall and at axial locations up to 9.0 m from the injector.

Particle eddy diffusivities were obtained from these measurements by using the relationship:

$$R_R = \frac{R_I U_o}{4\pi R_A \varepsilon_p x} \; e \; \frac{-\,U r_s^2}{4\varepsilon_p x} \qquad (12)$$

where

R_R was the local mass ratio of droplet material to air,
R_I was the material injection rate,
R_A was the air mass velocity,
x was the axial distance,

and r_s was the radial distance to the sampling position.

If the relationship r_s^2 vs R_R was plotted on semi-logarithmic coordinates then the diffusivity was obtained from the slope of the curve.

Figs. 11 and 12 show experimental measurements of, ε_p, non-dimensionalized with the fluid viscosity, ν, as a function of; the non-dimensional radial distance parameter y^+, and the particle diameter, d_p, at $Re = 2.64 \times 10^4$ and 1.27×10^5 respectively. Also shown on each figure are the theoretically predicted values of ε_p/ν, shown by solid lines, which have been derived from the following function;

$$\log \varepsilon_p/\nu = \log B_1 Re^{B_2} dp^{B_3} - \\ - \log B_4 Re^{B_5} dp^{B_6} (\log y^+ Re^{B_7} dp^{B_8})^2 \qquad (13)$$

where $B_1 - B_8$ were constants derived from a non-linear least squares analysis of practically obtained data.

An experimentally derived relationship between the eddy diffusivities of the fluid and the particle respectively is shown in fig. 13 where the Schmidt number, Sct, $= \varepsilon_F/\varepsilon_p$, was plotted as a function of, τ/T_1, where, T_1 was the Lagrangian macroscale of the fluid turbulence which was estimated from

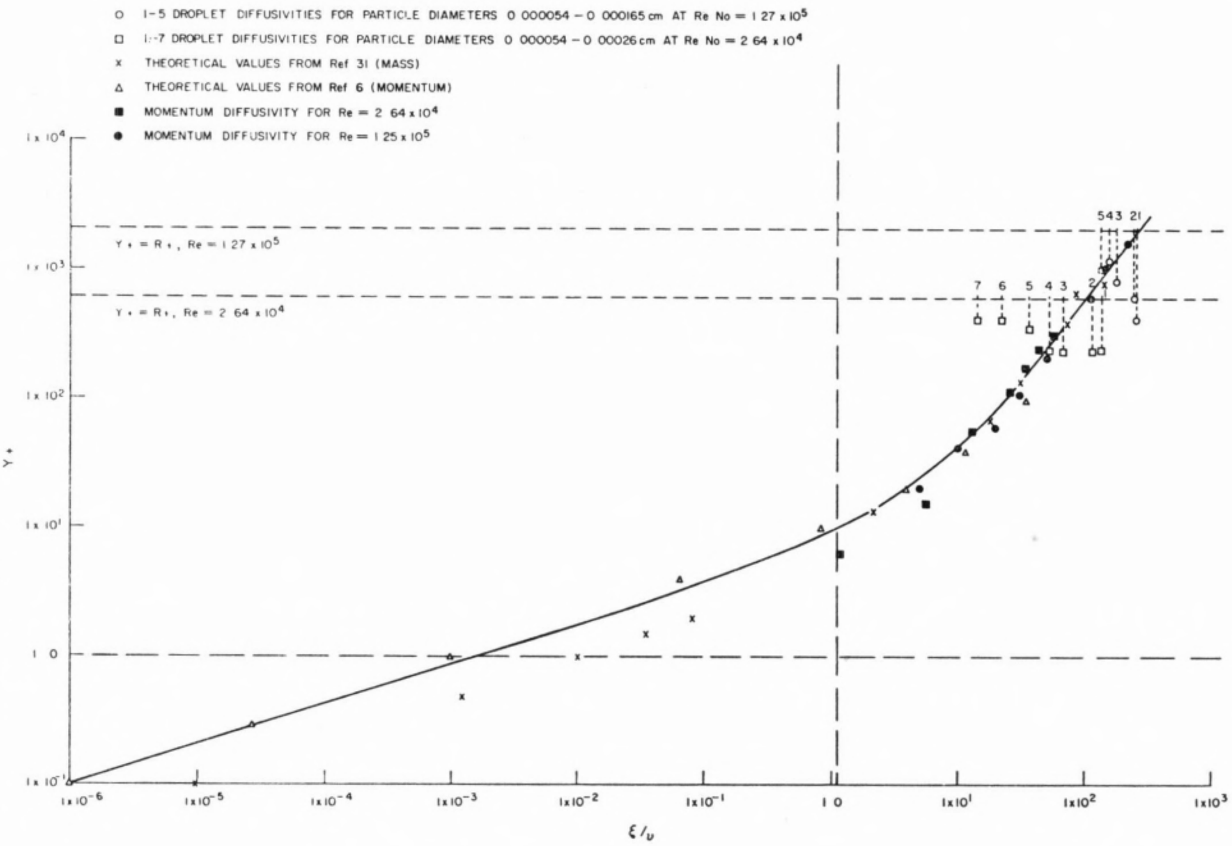

Fig. 14
The eddy diffusivities of mass and momentum

Table 1

Velocity amplitude ratio for droplets in fully developed turbulent pipe flow

Reynolds number	Particle size µm	Frequency c/s	Velocity amplification V_p/V_a
	1.0		0.9998
1.27×10^5		760.0	
	5.0		0.9174
	1.0		1.0000
2.64×10^4		188.0	
	5.0		0.9942

it's relationship to, momentum eddy diffusivity and the turbulent fluctuating velocity.

$$T_1 = \varepsilon_F/\upsilon'^2 \tag{14}$$

The particle relaxation time represented the decay with time of the velocity of a particle when it was injected into a quiescent fluid; the Lagrangian macroscale was a measure of this average time over which a fluid moved in one direction, therefore the ratio, τ/T_1, was regarded as a particle inertia parameter.

The results shown in fig. 13 indicated that as Reynolds number increased the Schmidt number decreased, which suggested that the particle diffusivity increased at a higher rate than the fluid diffusivity. The effect was reinforced by the tendency

Table 2

Comparison of relative turbulent intensities

Reynolds number	r'/a	u'/Uo	
1.27×10^5	0.1	0.079	
1.27×10^5	1.0	0.029	
2.64×10^4	0.1	0.069	
2.64×10^5	1.0	0.021	
5×10^5	0.1	0.070	(after Laufer)
5×10^5	1.0	0.027	
5×10^4	0.1	0.081	
5×10^4	1.0	0.027	

of the macroscale to increase with an increase in Reynolds number. The results were however at variance with the simplified theoretical results shown in Table 1.

A further illustration of the deviation between the diffusivities of mass and momentum is shown in fig. 14, where experimentally obtained values of the diffusivities of a range of particle sizes from 0.000054 — 0.00026 cm at $Re = 1.27 \times 10^5$ and 2.64×10^4 respectively are shown as a function of y^+. The lower values of y^+ were obtained from a theoretical correlation suggested by HUGHMARK [31]. Also shown on the figure are our experimental diffusivities for momentum at each value of Reynolds number respectively. Extrapolation of these results to low values of y^+ was carried out using the correlation of LIN *et al.* [6]. From the work on diffusivity it was clear the eddy diffusivity in Eqn. 2 depended upon

(i) y^+
(ii) Reynolds number

and

(iii) the droplet diameter.

The deposition velocities for droplets of the following sizes:

(i) 0.000054 cm diameter
(ii) 0.000060 cm diameter
(iii) 0.000094 cm diameter
(iv) 0.0001375 cm diameter
(v) 0.000165 cm diameter
(vi) 0.0002 cm diameter

and

(vii) 0.00026 cm diameter

were determined by carrying out a mass balance along the duct at $ReNo = 1.27 \times 10^5$ and $ReNo = 2.64 \times 10^4$ respectively.

The deposition velocity, K, was calculated from the following relationship;

$$K = -\left[\ln (C/Co)\ ({}^{Uo}/4)\ ({}^{a}/x)\right] \tag{15}$$

where the droplet concentrations at the inlet and downstream positions were Co and C respectively.

Fig. 15 shows the relationship obtained between the deposition velocity and the droplet diameter at: $Re = 1.25 \times 10^5$ and 2.64×10^4 respectively with a pipe wall temperature of 294 °K.

An exponential rise in the deposition velocity with

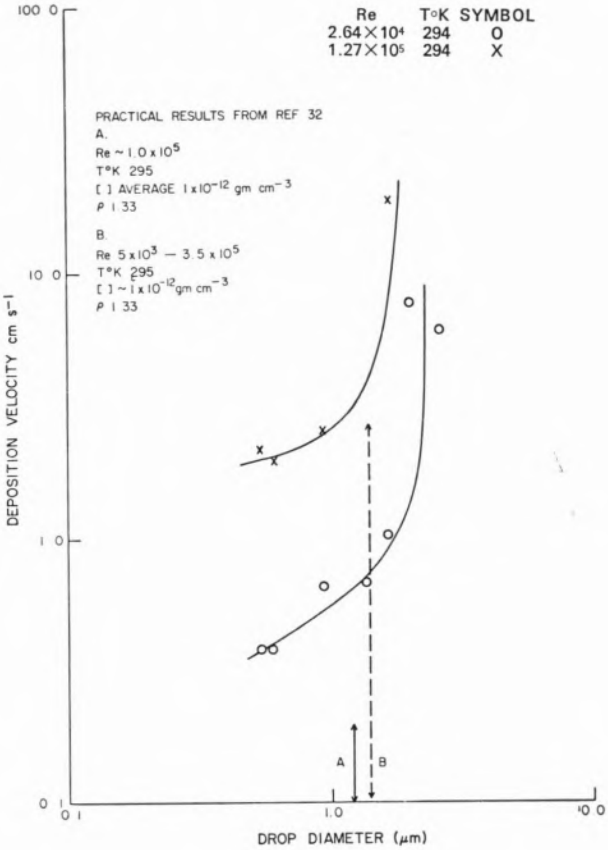

Fig. 15
Droplet deposition velocities as a function of size and concentration

an increase in this particle size was observed. For comparison, some experimentally obtained deposition velocities of ~ 1 μm diameter uranine particles, obtained by MONTGOMERY and CORN [32], are shown on the figure. The velocities obtained in our experiments were considerably higher, however this may have been due to the significantly higher particle mass concentrations used in our work; $8 \times \times 10^{-8}$ gm cm^{-3} compared with 1×10^{-12} gm cm^{-8} used by MONTGOMERY and CORN [32].

Figs. 11 and 12 showed an apparent decrease in eddy diffusivity with an increase in the particle size. This may be explained as follows: if we consider the injection of a small particle at the centre line of a turbulent pipe flow system, the particle will travel towards the pipe wall.

Work by SHAW and HANRATTY [33] and POPOVICH and HUMMEL [34] respectively, has shown that low momentum fluid was continually transferred, at convective velocities approximately equal to the friction velocity, towards and away from the wall within a region:

$$0 < y^+ < 2.0$$

in turbulent boundary layer flow. It is suggested that the droplet would approach to within a distance of $\sim y^+ = 2.0$ when the eddy in which it was entrained was met by an outflow of fluid from this wall, then, at the interface of the incoming and outgoing fluids, this resultant velocity might be zero. If the particle was of the order of 0.000054 cm diameter, and the transverse fluid velocity was of the order of $0.8\ U_\tau$, then at $Re = = 1.27 \times 10^5$, $ds^+ = 0.024$ so that the particle could not penetrate far into the wall region due to it's own inertia and was probably re-entrained into the core of the flow. In this way a low concentration gradient across the duct was rapidly set-up and since the effective diffusivity was an inverse function of the magnitude of this concentration gradient, a high value for ε_p resulted. If a droplet which had a diameter of 0.00026 cm had been considered, then at the interface of the fluids $ds^+ = 0.56$, so that, due to its own inertia the droplet travelled well into the final wall region where, statistically, the probability of it reaching the wall due to entrainment by fluid returning to the wall in this highly perturbed region, was high.

From the foregoing it is clear that the larger particles were removed more rapidly from the turbulent core than the smaller ones, this was supported by the results shown in fig. 15, the effect was manifested in a high radial concentration gradient with a consequent low eddy diffusivity value. In conclusion, measurements of the eddy diffusivity of mass and momentum in fully developed turbulent pipe flow have been made, and in practice the ratio, $\varepsilon_f/\varepsilon_p$ effectively increased with particle size due partly to this definition of diffusivity, but decreased with an increase in Reynolds number which indicated that the mass diffusivity increased more rapidly than momentum diffusivity under these conditions.

A theoretical relationship between the non-dimensionalized eddy diffusivity of mass, ε_p/υ, and the wall distance parameter, y^+, has been derived, as a function of:

(i) the droplet size and
(ii) Reynolds number

which appeared satisfactory within the limits,

$$1.5 < y^+ < R^+.$$

Droplet deposition velocities have been measured for a range or particle sizes and flow conditions. The deposition velocity increased with ReNo, and increased exponentially with the particle size. A tentative qualitative theory of deposition has been suggested, which was supported by the measurements that have been made.

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ACKNOWLEDGEMENT

The authors wish to acknowledge the financial and technical assistance of Shell Research Limited which enabled the completion of this work.

RESUMO

Discutem-se diversas metodologias para o cálculo da velocidade de deposição de partículas sobre as paredes de tubagens percorridas por fluidos em escoamento turbulento. A necessidade de tomar em consideração as relações entre as difusividades turbulentas de massa e de quantidade de movimento é indicada e quantificada experimentalmente. Considerando-se que o escoamento é bidimensional a sua caracterização é feita através dos valores da velocidade média na direcção radial e da raiz quadrada média das flutuações de velocidade na direcção axial, assim como da distribuição da tensão de corte. A partir do último estima-se a difusividade turbulenta do fluido. As medições foram feitas a números de Reynolds de 1.27×10^5 *e* 2.64×10^4 *sendo a temperatura da parede 294,0 °K. Injectaram-se na corrente fluida gotas de di-2-etilhexilsebaceato de diâmetros compreendidos entre 0,54 e 2,6* μ*m e mediram-se as suas velocidades de deposição, tendo-se observado que esta crescia com o aumento da dimensão da partícula e do número de Reynolds.*

A. ARROWSMITH
University of Birmingham — U. K.

P. J. FOSTER
University of Sheffield — U. K.

FLUID ENTRAINMENT AND DRAG REDUCTION BY STREAMS OF LIQUID DROPS FALLING THROUGH GASES OR LIQUIDS (1)

Predictions of transfer phenomena in dispersed phases which are based on single particle behaviour are limited in applicability because they do not consider the interaction between particles themselves and with the surrounding fluid. A theoretical analysis is presented in this paper which describes fluid entrainment by a single stream of droplets and the effect of this boundary layer flow on subsequent drop motion. The predicted effects are compared with experimental measurements of droplet velocities in streams moving through gaseous and liquid environments.

1 — INTRODUCTION

The interaction of a spray of liquid drops with a gaseous or liquid environment is a complex phenomena which has consequently received little theoretical study. Such sprays are of considerable industrial importance and cover a wide range of characteristics, varying from small diameter high velocity droplets moving through high velocity air streams, typically combustion sprays, to large diameter low velocity droplets moving through low velocity liquids, typically sprays used in solvent extraction. Some sprays are produced deliberately to promote transfer processes by increasing surface area and mixing, while others are unwanted by products formed through such processes as boiling, splashing and condensation.

Common to all of these processes is the need to predict the time and distance of travel of the dispersion to undergo a required transfer of heat mass or momentum.

Predictions of spray droplet characteristics have centered around two approaches:

(i) the identification and representation of the factors influencing transfer processes between single droplets and an infinite environment;

(ii) empirical correlations resulting from measurements of particular spray properties with varying operating conditions.

The majority of reported correlations to describe heat and mass transfer from single droplets have been of the form

$$\left.\begin{array}{l} \mathrm{Nu} = \mathrm{f}\ (\mathrm{Re},\ \mathrm{Pr}) \\ \mathrm{Sh} = \mathrm{f}\ (\mathrm{Re},\ \mathrm{Sc}) \end{array}\right\} \qquad (1)$$

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(1) Presented at CHEMPOR' 75 held in Lisbon, 7-12 September 1975 at the Calouste Gulbenkian Foundation Center.
Papers presented at this International Chemical Engineering Conference can be purchased directly from Revista Portuguesa de Química (Instituto Superior Técnico, Lisboa 1, Portugal) at the following prices per volume sent by surface mail, postage included (in Portuguese Escudos):

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Management studies	150

This paper was presented at the Transport processes section.

The relationship depending upon the type and range of the experimental studies [1]. The flow around a droplet is therefore important in defining these transfer processes, as well as predicting its motion.

The velocity of a droplet may be calculated from a force balance on it

$$\begin{matrix}\text{Net}\\ \text{Force}\end{matrix} = \begin{matrix}\text{Gravity}\\ \text{Force}\end{matrix} - \begin{matrix}\text{Bouyancy}\\ \text{Force}\end{matrix} - \begin{matrix}\text{Drag}\\ \text{Force}\end{matrix} \qquad (2)$$

The difficulty in the application of the balance arises with the drag force, which is usually expressed in terms of a drag coefficient

$$\text{Drag Force} = \frac{C_d \rho_a V^2 A_p}{2} \qquad (3)$$

Many results have been published from studies on the prediction or measurement of drag coefficient and the factors such as drop acceleration, oscillation, distortion, rotation, internal circulation, mass transfer and flow turbulence intensity which effect it [2, 3, 4]. The range of coefficients reported depend upon the flow regime and vary from simple functions of Reynolds number, which may be applied over a wide range with limited accuracy, to more complex relationships, which are more accurate over a limited range. The selection of a suitable one for a particular application may be a compromise between accuracy and the ease of mathematical manipulation.

For use over a range of Reynolds numbers typically encountered in sprays the following coefficient was used with accuracy and convenience [5]

$$C_d = \{23 + (1 + 16\mathrm{Re}^{4/3})^{1/2}\}/\mathrm{Re}$$
$$\text{for } 1 < \mathrm{Re} < 500 \qquad (4)$$

Equations (1)-(4) enable the history of a spray droplet to be calculated as it passes through a reactor if the properties of the flow surrounding it, characterised by the Reynolds number, are known.

In most applications the droplets are members of polydisperse sprays and from a knowledge of their size distribution [6], it is possible to sum their effect on the overall spray behaviour. There is, however, an interaction between the droplets and between the spray and the surrounding atmosphere, such that the transfer potentials around any individual droplet are uncertain. This uncertainty leads to error in applying single droplet data to the description of sprays.

Interactions between droplets falling in single streams, horizontal assemblages and sprays through liquids have been measured by RAGHAVENDRA and RAO [7]. For this low Reynolds number situation they have found that interaction between droplets in a horizontal plane lead to increased drag while interaction between droplets in a vertical plane resulted in reduced drag and increased terminal velocities. The extent of the deviation was a function of the droplet separation.

ZABEL *et al.* [8] similarly observed a reduction in drag coefficient, of up to 50 %, for drops falling in single streams through stagnant liquids, when compared with single droplet results.

Direct measurements of spray properties have resulted in empirical correlations [9] which are valid for simple sprays, but the variation in droplet sizes and velocities, nozzle types and operating parameters precludes their general use.

More recently attempts have been made to understand these interaction effects for high Reynolds number flows, for liquid sprays in air, in terms of momentum transfer. Observations of the air flow pattern around a hollow cone spray [10] indicated that the flow was induced to enter the spray at right angles to the surface as a result of momentum transfer from the droplets. While passing through the spray the air flow changed to a direction parallel to the nozzle axis and in so doing entrained droplets, moving them into the hollow core. Using such a model, Benatt and EISENKLAM [11] have predicted air entrainment factors for swirl nozzles spraying water into air at ambient conditions. The theoretical and experimental results indicated that entrainment was proportional to spray angle, but there was constantly 25 % difference in the two values over the entire range of results.

From force and momentum balance, across an element of a flat spray BRIFFA and DOMBROWSKI [12] have predicted air entrainment using a theoretical treatment which requires a knowledge of the drop size distribution and the initial drop velocities. Their results show good agreement with measured flows into iso-octane and tetralin sprays for a wide range of nozzle pressure drops.

To overcome the problems associated with applying single drop theory to sprays an approach based on continuum mechanics was used by ADLER and LYN [13] to predict the steady evaporation and mixing of a liquid spray injected into a gaseous swirl. Some experimental data is however required in order to simplify numerical solution of the diferential transfer equations.

These theoretical approaches are all limited in that they describe particular practical situations and do not assess the fundamental processes common to any form of dispersion, or the situations which they describe are complex and do not allow experimental measurement of the parameters which are either theoretically predicted or are empirical constants in the theoretical model.

In this paper the authors describe a more general approach to the problem of assessing interaction effects, by a study of the motion of a single stream of liquid droplets moving at a constant frequency.

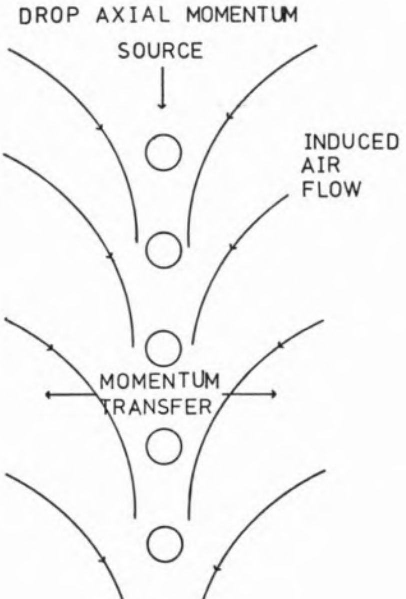

Fig. 1
Drop stream and induced air flows

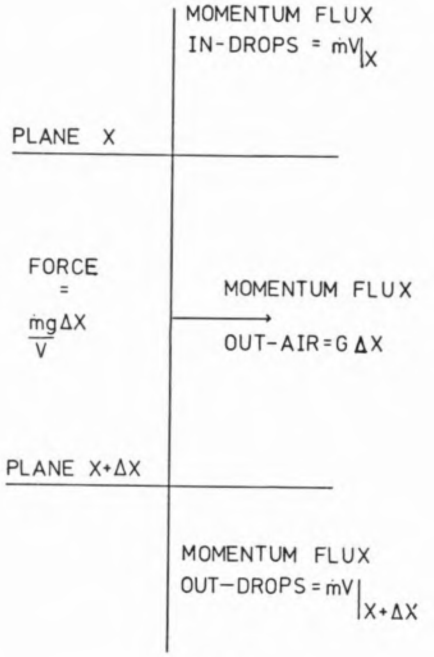

Fig. 2
Force momentum balance along drop stream axis

The stream constitutes a source of momentum in the ambient fluid, which results in a boundary layer flow being induced around it. The momentum transfer is predicted using a theoretical treatment similar to that of ADLER and LYN [13], and the simplicity of the experimental technique enables accurate measurements to be made for comparison with the theory.

2 — THEORY

The theoretical analysis considers the stream of droplets, moving at a constant frequency to be a continuous source of axial momentum with the time averaged properties of the intermittent flow. Momentum is transferred from this source to the surroundings and induces an axisymmetric flow around the stream, fig. 1. The steady laminar flow of a Newtonian fluid within this boundary layer is described by the integral form of the equation of motion

$$\rho_a \frac{\partial}{\partial x} \int_{r=0}^{r=R} r u \left(u - u(R)\right) dr = \mu \left[r \frac{\partial u}{\partial r} \right]_{r=0}^{r=R} \tag{5}$$

The source of x-momentum is related to the viscous shear expression in equation (5) by

$$G = -2\pi\mu\left[r\frac{\partial u}{\partial r}\right]_{r \to 0} \tag{6}$$

and G is given by a force, x-momentum balance, fig. 2

$$G = \left(1 - \frac{\rho_a}{\rho_p}\right)\frac{\dot{m}g}{V} - \dot{m}\frac{dV}{dx} \tag{7}$$

The axial drop velocity gradient is specified by a force, momentum balance on an individual drop

$$\frac{dV}{dx} = \frac{3C_d\rho_a}{4D_p\rho_p}\frac{(U-V)^2}{V}\frac{(U-V)}{|U-V|} + \frac{g}{V}\left(1 - \frac{\rho_a}{\rho_p}\right) \tag{8}$$

The radial profile of axial velocity in the boundary layer is assumed to be of the form

$$u(x, \eta) = U(x)F(\eta) \tag{9}$$

where

$$\eta = \frac{r}{b}$$

The integration of the boundary layer equation of motion from the axis to infinity and from the axis to the radius of half maximum air velocity, results in two differential equations which when combined with equation (8) and solved simultaneously enable the drop velocity, air velocity and boundary layer width to be predicted. The approach follows a procedure adopted by SQUIRE and TROUNCER [14].

The numerical integration requires the specification of the initial drop and air stream parameters, V(x), U(x) and b(x) at $x = 0$ and the form of the velocity profile in the boundary layer $F(\eta)$.

3 — RESULTS

The ability of the theoretical analysis to predict the motion of droplets moving in a stream, through a gaseous or a liquid environments, has been assessed by comparison with experimental measurements.

Single streams of water droplets, moving at a constant frequency, were produced by the longitudinal vibration of a liquid jet [15]. A droplet was produced during each oscillatory cycle thus producing a time base for measurements of drop velocity. Droplet diameters and interdrop distances were recorded photographically as the drops fell under gravity through a 25 cm long perspex box fitted with optical windows. Drop diameters varied from 250-1250 μm, initial velocities from 1 to 5.5 ms^{-1} and frequencies from 100 to 5000 drops s^{-1}.

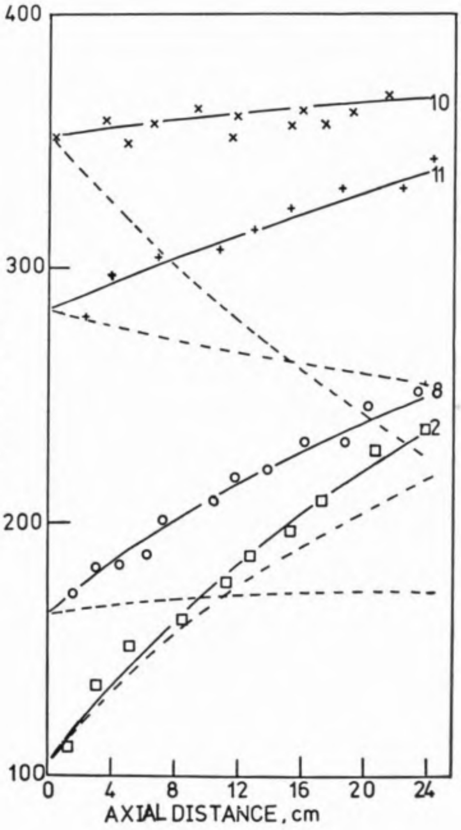

Fig. 3

Measured × + ○ □ *and predicted stream* —— *and single drop* – – – *velocities*

A comparison between measured stream drop velocities, those predicted by the theoretical analysis from the same initial stream conditions and theoretical predictions for a single drop are shown in fig. 3. The four sets of results cover a range of experimental conditions with increasing deviation from single drop behaviour. The experimental parameters of these curves are given in Table 1. The curves in fig. 3 illustrate that the stream drop motion is well predicted by the theory when the motion is similar to that of a single drop and also when there is a considerable difference between the motion of a single drop and a stream of drops with the same initial velocity.

To provide further support for the theoretical treatment air velocities were measured in the entrained boundary layer from a hot-wire anemometer traverse. Evidence of the existence of this entrained flow is provided in fig. 4 which shows a titanium tetrachloride smoke tracer emanating from a wire held near to the stream.

Table 1

Experimental data for fig. 3

Run No.	Initial drop velocity, ms^{-1}	Drop diameter mm	Drop frequency, s^{-1}
2	1.056	1.18	234
8	1.638	0.448	1257
10	3.518	0.380	1736
11	2.827	0.555	1377

The length of the hot-wire anemometer probe used in these measurements was 1200 μm, somewhat larger than the drop diameter and comparable to the width of the boundary layer. Thus the air velocity was not constant over the length of the wire and the output of the anemometer then represented some mean value interpretation. A theoretical treatment has been developed for the prediction of the radial profile of axial velocity from such a traverse through an axisymmetric flow [16].

An energy balance across the wire gives

$$\frac{d^2T}{dx^2} + Ai^2 + (Bi^2 - C)(T - T_a) - D(T - T_a)f(x)^{\frac{1}{2}} = 0 \qquad (10)$$

where ABC and D are constants given by the physical properties of the wire and f(x) is the velocity over the wire. The boundary conditions are $dT/dx = 0$ at $x = 0$, the mid-point of the wire and $T = T_a$ at $x = 1$, the end of the wire attached to the probe support. It was assumed that f(x) could be represented by a parabolic distribution along the wire. Equating the mean temperature of the wire in such a parabolic flow with that from a uniform velocity across the wire enables the mean velocity interpretation in an axisymmetric flow to be converted to a radial velocity profile if the width of the distribution is known.

An example of the non-uniform flow across a wire during a radial traverse is shown in fig. 5 and the transformation of the anemometer readings into a radial velocity profile is shown in fig. 6.

There is a general agreement between measured values of air velocity and boundary layer width and those predicted by the stream entrainment theory. The transformation of anemometer results requires an input conditions for the numerical integration and this is most conveniently provided at present by the maximum air velocity given by a linear approximation analysis of the transformation, reported earlier [17], or by the drop stream velocity. Accepting the limitations of the analysis, which is being further investigated, air velocities agree within ± 10 % and boundary layer widths are also comparable.

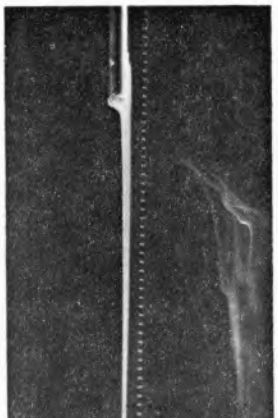

Fig. 4
Entrainment of a smoke tracer by the drop stream

The results from the studies of the motion of a stream of liquid droplets through air demonstrate the importance of the entrained air flow in predicting droplet trajectories, and provide an explanation for the observed deviations from the standard drag relationships which have been reported by several workers.

The ability of the theory to describe the motion of liquid streams moving through liquids has been assessed by a comparison with the experimental results of other workers.

Raghavendra and Rao [7] measured the terminal velocities of nitrobenzene drops falling in single streams through water. Drop diameters were varied from 0.2 to 0.6 cm, frequencies from 3 to 4 drops s^{-1} and measured terminal velocities varied from 9 to 18 cm s^{-1}. Terminal stream drop velocities predicted by the theory

$$V_s = \frac{1}{2}\left(V_t + (V_t^2 + 0.093\, g f D_p^3(\rho_p - \rho_a)/\mu)^{\frac{1}{2}}\right) \tag{11}$$

are compared with the above experimental results in fig. 7. It is seen that there is an approximate agreement over this narrow range of drop diameters.

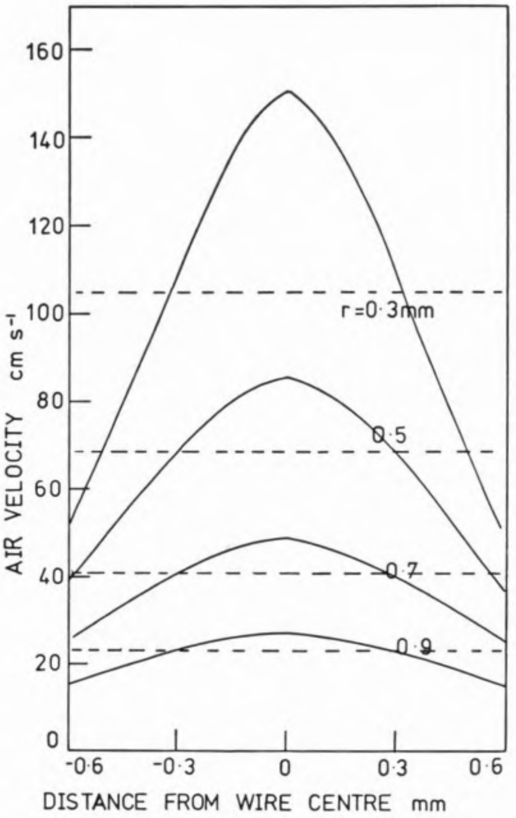

Fig. 5

Variation in velocity distribution along hot-wire with radial position-r

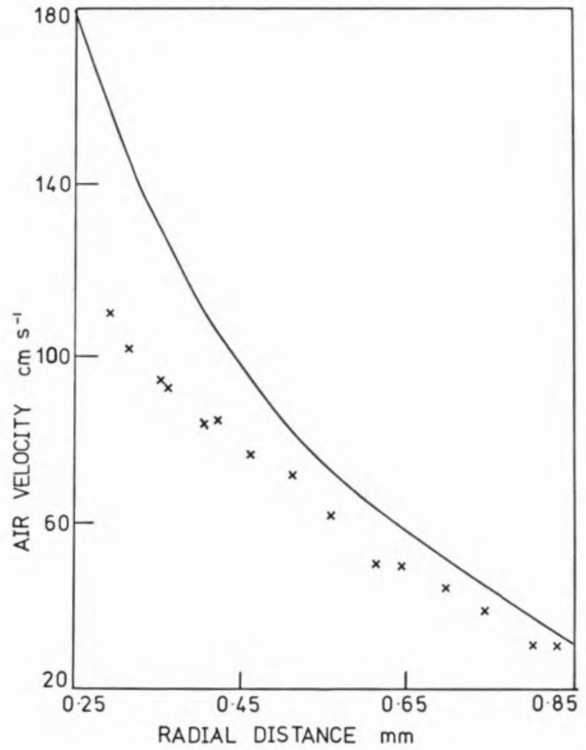

Fig. 6

Transformation of anemometer readings × into a radial velocity profile ——

The predicted values are based upon a standard curve drag coefficient for solid spheres, equation (4), and cannot take into account the effects caused by drop distortion which occur at Reynolds numbers above 200 [18]. The increased drag which results from the drop distortion is manifested in terms of a reduced terminal velocity over the whole range of drop diameters used in these experiments. Thus although the reduction in drag resulting from stream motion is evident, it is not possible to quantitatively compare the two sets of data.

The reduction in drag coefficient experienced by droplets moving in a stream through a liquid was also measured by Zabel *et al.* [8]. Cine photography was employed to record the motion of 0.33 cm diameter drops of carbon tetrachloride as they travelled through water-glycerol solutions of various concentrations.

For drops moving at their terminal velocity the drag coefficient is given by

$$C_d = 4(\rho_p - \rho_a)D_p g/3\rho_a V_t \tag{12}$$

and the drag coefficient for droplets moving in a stream, based on their absolute velocity, can therefore be related to that for a single drop by

$$C_{ds}/C_d = V_t^2/V_s^2 \tag{13}$$

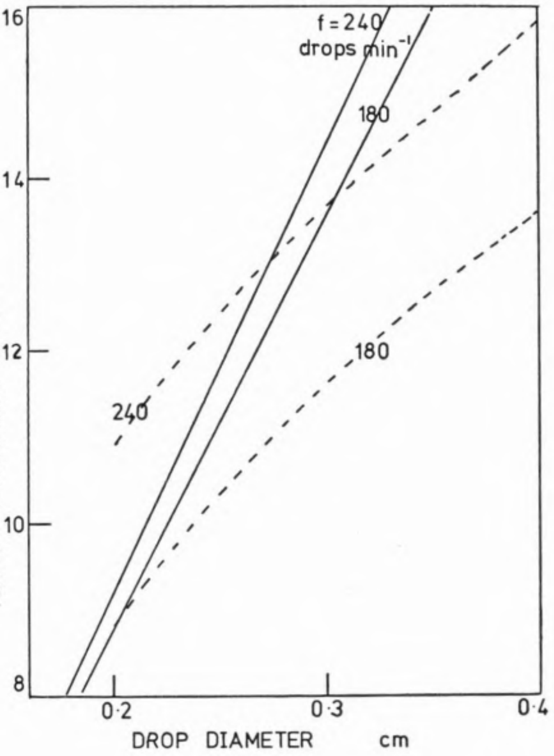

Fig. 7
Predicted —— and measured – – – drop stream terminal velocities

Equations (11), (12) and (13) can be combined to predict the reduction in drag coefficient experienced by stream droplets

$$C_{ds}/C_d = 4(1 + (1 + 0.07\, C_d Re D_p/L)^{\frac{1}{2}})^{-2} \tag{14}$$

and the results compared with the experimental data of Zabel *et al.* [8] and Raghavendra and Rao [7], as shown in fig. 8. It is clear that both experiment and theory demonstrate reduced drag as a result of stream motion, but also that the theory underestimates the effect for Re < 150 and overestimates for Re > 150. This closely reflects the comparison of single drop motion with that of a single solid sphere, where at low Reynolds numbers the drag on a sphere is reduced by internal circulation and at higher Reynolds numbers the effects of drop distortion lead to irregular movement and increased drag. These effects appear to be amplified in streams [8].

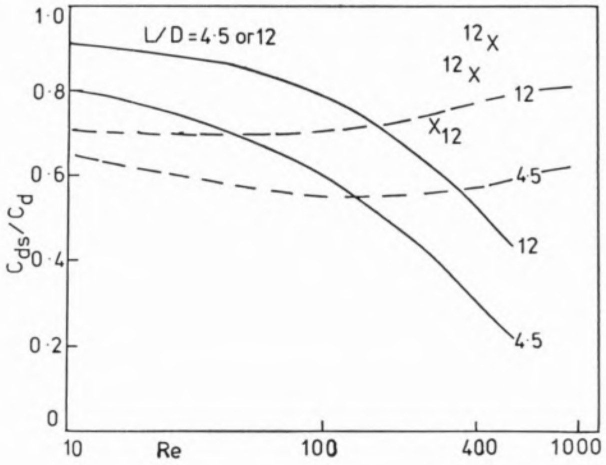

Fig. 8
Reduction of drag coefficient for stream drops, predicted ——, measured by Zabel – – –, and by Raghavendra ×

4 — CONCLUSIONS

The entrainment of the ambient fluid by a stream of drops and the formation of a boundary layer significantly reduces the drag experienced by the droplets and correspondingly increases their terminal velocity. The results imply that the accurate prediction of transport phenomena in dispersed phase systems necessitates the inclusion of terms to account for this flow, and suggests that discrepancies reported between drag data from single particle studies and measurements on spray system may be due to this effect.

NOMENCLATURE

A,B,C,D — constants which depend upon the physical properties of hot-wire probes
A_p — projected area of particle
b — radius of half maximum air velocity
C_d — drag coefficient
C_{ds} — drag coefficient for a stream drop based on absolute velocity
D_p — drop diameter
f — drop stream frequency
f(x) — velocity along hot-wire
g — gravitational acceleration
G — average rate of production of x-momentum per unit length of drops stream
i — current flowing through hot-wire
l — lenght of hot wire
L — interdrop distance
m — mass flow rate of drops
Nu — Nusset number
Pr — Prandtl number
r — radial distance co-ordinate
R — specific radial distance from axis
Re — Reynolds number
Sc — Schmidt number
Sh — Sherwood number
T — wire temperature
T_a — ambient temperature
u — air velocity in the x-direction
U — maximum average air velocity
V — drop velocity
V_t — terminal velocity of a single drop
V_s — terminal velocity of a stream drop
X — axial distance from the origin of the drop stream

GREEK SYMBOLS

η — dimensionless radial co-ordinates, r/b
μ — viscosity of ambient fluid
ρ_a — density of ambient fluid
ρ_s — particle or drop density

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RESUMO

As previsões de fenómenos de transporte em fases dispersas que se baseiam no comportamento de partículas isoladas têm uma aplicação limitada na medida em que não consideram as interacções das partículas entre si e com o meio fluido vizinho. No presente artigo apresenta-se uma análise teórica em que se descreve o arrastamento do fluido provocado por uma corrente de gotas e o efeito deste movimento do tipo camada-limite no movimento de gotas subsequentes. As previsões teóricas são comparadas com medições experimentais de velocidades de gotas — em correntes — através de meios líquidos e gasosos.

P. C. LAMBERT (1)
G. H. COWAN (2)
T. R. BOTT (1)

(1) Department of Chemical Engineering
University of Birmingham
P. O. Box 363
Birmingham B15 2TT
England

(2) Heat Transfer and Fluid Flow Service
Thermodynamics Division
Building 392
A.E.R.E., Harwell, Didcot, Oxon
OX11 ORA, England

THE EFFECTS OF FAN AND PLENUM PARAMETERS ON THE AERODYNAMIC PERFORMANCE OF A MODEL AIR COOLED HEAT EXCHANGER (3)

Using a flow visualisation technique, hot wire anemometer and Kiel probe measurements, air flow characteristics of a model air-cooled heat exchanger have been studied.

With box type plenum chambers the results indicate that a central core of rotating air exists with large areas of recirculating flow below the reattachment points particularly in the corners. Certain configurations using a low hub/tip ratio fan gave significant backflow close to the hub. A shaped plenum removes the corner recirculating flow. For the system tested, design features such as a deep fan ring, uniformly shaped fan blades with a relatively large streamlined hub increase the efficiency of the fan and exchanger.

It is concluded by comparison that a square plenum is better than a rectangular plenum. For a square plenum the optimum height appears to be about half the fan diameter for forced draft units.

The prediction of air flow characteristics of large air cooled heat exchangers by computer is anticipated in the future.

1 — INTRODUCTION

Until the beginning of the last decade, any method of process cooling in the chemical and petroleum industries, other than water cooling was considered exceptional, with the result that very little money was spent investigating these 'fringe' methods. It was only in countries where water was in short supply — and hence costly — that the operating costs involved could be compared favourably with water cooling costs. Since the late nineteen fifties however, two factors have combined to cause air cooling to be considered more and more favourably. These two factors are the huge increase in oil refining and chemical manufacturing capacity, and the advent of increased public concern about the environment.

The sudden rise in demand for process cooling led to increased water costs, while concern about the purity of water being returned to rivers and seas necessitated the building of further processing plant for water treatment. As a result of this sharply increased cost of cooling water, air cooling is capable of competing economically and many industrial companies now use air colling in preference to water cooling.

The reason for the use of air-cooled heat exchangers is their simplicity. An air-cooled heat exchanger consists of a low speed axial flow fan forcing air across a bank of finned tubes through which the fluid to be cooled flows. A plenum chamber connects the fan and tube bundle. The fan may be placed either above or below the tube bundle, when the cooler is said to be induced draught or forced draught respectively. Induced draught cooling suffers from the disadvantages of being more costly

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(3) Presented at CHEMPOR' 75 held in Lisbon, 7-12 September 1975 at the Calouste Gulbenkian Foundation Center.

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to run (since the air is at a higher temperature, a greater volume of air is involved) and the need for large structures to support the fan motor. Forced draught cooling provides a much poorer flow distribution over the tube bundle.

In general, each fan is between 6 ft. and 16 ft. in diameter, and supplies air to a finned tube area approximately 2½ times the fan swept area. These large fans commonly have 4 to 6 or even 8 blades and the tip speed of a blade is unlikely to be above 10,000 ft./min; and probably much lower. The power requirement of a large fan can be up to 50 H.P. and because of this, for fans above 8 ft. in diameter, direct drive (where the motor is fixed immediately above or below the fan hub) is seldom used. The motor is then located nearby and the drive transmitted to the fan by belt or gears, the latter being more suitable for very large power requirements. In almost all cases the tube bundle will have between 3 and 8 rows of finned tubes.

In the design of an air-cooled heat exchanger, the parameters are all concerned with the process fluid — namely how much heat must be removed. Allowing for available pressure drop on the process side, a tube bundle can be designed. From the data available on flow over finned tube banks, and heat transfer coefficients for finned tubes, a volumetric air flow can be calculated along with an air-side pressure drop to achieve the stipulated heat loss. With this information a suitable fan could be selected.

The final stage is to specify the plenum chamber design. Since a transition from a circle to, generally, a rectangle is involved, there are an infinite number of shapes possible. Common practice is to use a box shape of the same cross-section as the tube bundle and attach the fan at the centre of the base of the plenum.

There are empirical rules for the specification of air-cooled heat exchangers [1], but a better understanding of flow characteristics in such units is required before greater confidence can be placed in design procedures. This paper describes experimental work to determine the effects of fan and plenum parameters on the aerodynamic performance of a model air-cooled heat exchanger. The work involved detailed measurements of airflow in the plenum of the exchanger and the variation of the airflow characteristics with changes in design.

2 — PRELIMINARY STUDY

At the outset of the work, a literature search quickly indicated that the available information could be divided into two distinct sections, dealing with the air-cooled heat exchanger as a complete entity, and the constituent parts. The survey revealed the lack of previously published information on the aerodynamic performance and characteristics of air-cooled heat exchangers from the standpoint of air-side efficiency. There is however a larger amount of information available on the fan and plenum chamber as separate entities, the latter being considered to be a diffuser.

The literature on axial flow fans is varied ranging from detailed computer design to noise generation [2 to 11]. A recently published text gives a detailed review of axial flow fans [12]. A major factor which governs both pressure rise and velocity distribution, and which is not dependent on fan design (but mainly on fan blade setting and manufacturing tolerances) is the tip clearance — the gap between the fan ring and the blade tip [6]. As a result of detailed wind tunnel investigations it was found that reduction in tip clearance resulted in increased fan performance.

With respect to plenum chambers it is first necessary to give some definitions. The plenum chamber is the name given to the enclosure between the fan ring and the outlet resistance of an air-cooled heat exchanger. It is common practice to refer to either the plenum chamber or the plenum both being identical. In this paper the plenum refers to the physical structure namely the sides and base, whilst the plenum chamber describes the space enclosed by the plenum. Generally two types, box and shaped, are used industrially. With a box plenum there is an abrupt expansion on entering the plenum chamber from the fan ring and the cross-section of the plenum is uniform.

The box plenum may be regarded as a diffuser of angle 90°, and by considering the performance of diffusers, some insight into the flow in a plenum chamber is possible. A large proportion of the literature is taken up with the problem of flow separation at the walls of a diffuser — this will inevitably occur with flow through a step expansion (in effect a box plenum) [13-17]. This separation causes a considerable increase in flow turbulence and hence an increase in pressure loss, which can become important in air-cooled heat exchangers. It has been noted that swirling flow helps to suppress this flow separation [18, 19], as does the addition of an outlet resistance [20], thus transforming the system to approximate to an air-cooled exchanger. The information available on the separate parts of the heat exchanger becomes more important because of the lack of published information on the detailed aerodynamic performance of the complete unit. The majority of papers referring to air-cooled heat exchangers are to their design or thermal rating generally expressed in terms of overall heat transfer coefficients based on the tube (process) side, while others discuss the economics of air and water cooling [21-25]. An integral step-by-step method for calculation of the thermal performance of air cooled heat exchangers is reported [26, 27].

The only references to air-side measurements were not to the design of the unit, but to the checking of the performance of operating units. A number of papers have been published describing air-flow measurements on industrial air-cooled heat exchangers [28-35]. Various methods for measurement of air-flow through air-cooled heat exchangers are discussed in these papers including

(*a*) single vane anemometer traverse at bundle outlet of forced draght units
(*b*) single vane anemometer traverse at fan inlet of forced draft units
(*c*) single vane anemometer tranverse at fan outlet of induced draught units
(*d*) use of an array of anemometers at bundle outlet and
(*e*) constant rate injection technique using the Kr_{85} isotope.

When checked against a heat balance on an exchanger the radioactive tracer technique appears to give the most accurate answer. The use of a multi-anemometer array at bundle outlet is useful for quickly determining airflow distribution.

The literature survey indicated the need for work to determine the effect of changing fan and plenum design parameters on the detailed aerodynamic performance of air-cooled exchangers and, if possible, to evolve methods of predicting such changes. The following sections describe equipment and testwork to try to fulfil partly this need.

3 — EQUIPMENT

The model air-cooled heat exchanger unit on which the majority of the testwork was performed was located in the open air. It was operated as a forced draught unit with isothermal flow. The unit was supported by 4 legs, the entrance to the plenum being 8 ft. 11 ins. from the ground (see fig. 1). The unit may be considered in three sections — fan, plenum and outlet resistance. The various combinations of these sections which were used in the experimental work are detailed below.

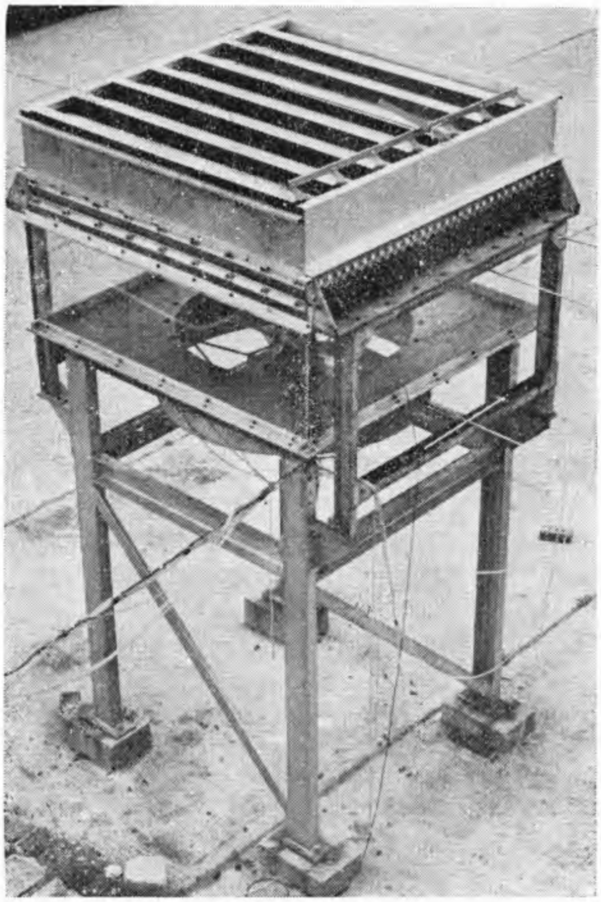


Fig. 1

3.1 — *THE AXIAL FLOW FANS, PLENUM AND OUTLET RESISTANCES*

During the course of the work two fans were tested, they are denoted by 4.167 and 4.375 representing the number of blades and the decimal

Table 1

Fan details

	Fan 4.375	Fan 4.167
Diameter	48 ins.	48 ins.
Rotational speed	720 r.p.m.	720/960 r.p.m.
Number of blades	4	4
Variable pitch	No	Yes
Blade angles	28.4°	5.5° — 28.4°
Blade shape	uniform	aerofoil
Blade thickness	uniform	aerofoil
Tip clearance	½ %	½ %
Depth of fan ring	20 ins.	8 ins.
Fan ring inlet	none	7½ ins. cone
Fan hub	hemispherical	planar
Fan-plenum distance	14 ins.	3 ins.
Hub diameter	18 ins.	8 ins.
Hub to tip ratio	0.375	0.167
Motor drive	direct	direct
Motor casing diameter	14 ins.	10 ins.

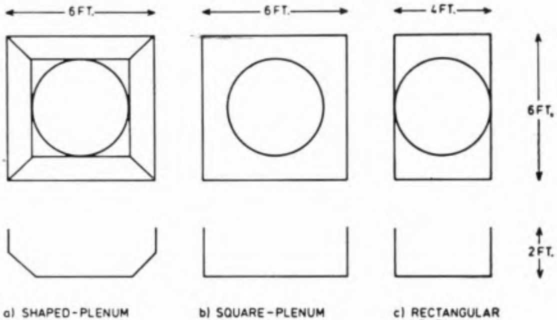
parts giving the hub-to-tip ratios. Further details of the fans are given in Table 1.

With the 4.375 fan tests were made using a box plenum chamber whereas with the 4.167 fan tests were made using both box and shaped plenum chambers. For the experimental work using a box plenum the sides were made of clear 'Perspex' so that visual observation could be made. The flow area was generally 6 ft. square, though some tests were performed with a rectangular plenum 6 ft. long and 4 ft. wide (see fig. 2). For the square section plenum the height of the plenum was also changed through the range 3 ft., 2 ft. to 1 ft. high. Care was taken to ensure that the inside of the plena were as smooth as possible with no interference to flow.

Two shaped plena were studied. One was a 6 ft. diameter cylinder 3 ft. high, which was fitted into the existing square plenum. The reason for choosing a cylindrical plenum was to give a symmetrical 2-dimensional geometry to allow experimental measurements to be compared with theoretical predictions. (No theoretical solution was available for fully three dimensional situations.)

The second shaped plenum (see fig. 2) was 2 ft. high overall of which only the first 1 ft. from the fan inlet was shaped, the second 1 ft. being 6 ft. square. The shaping was a section of a mild steel hollow regular pyramid 1 ft. high, 6 ft. square at the base and 4 ft. square at the top. It was placed inverted in the original 6 ft. square box plenum. No physical connection was made either to the base or sides of the plenum.

In industrial air-cooled heat exchangers the outlet resistance from the plenum for forced draft units is generally a bank of finned tubes. Outlet louvres may also be added to provide a controlling system for the air flow rate. In this paper the tube bundle



a) SHAPED-PLENUM   b) SQUARE-PLENUM   c) RECTANGULAR-PLENUM

Fig. 2

is referred to as the primary resistance and the louvres as the secondary resistance.

For the 4.375 fan a single layer of closely spaced smooth tubes were used as the primary outlet resistance. The tubes were made of aluminium 2 ins. o.d. and 6 ft. 3 ins. long. The spacing of the tubes was such that the resistance was approximately that of a finned tube bundle 4 rows deep. For the initial testwork with the 4.167 fan a finned tube bundle was used as outlet resistance. The tubes were located in header plates which could accommodate four rows but the resistance could be varied as required by removing a single layer of tubes. The tubes were of mild steel, 1 in o.d., with aluminium 'G' fins of 2.25 in o.d. and 11 fins per inch. A 2.30 in triangular pitch was used, and the tube bundle was 6 ft. square. The sides of the tube bundle were made of 'Perspex' and 90° angle brackets were fixed on the sides to simulate 'half-tubes'. No provision was made for liquid flow through the tube bundle. In order to change operating conditions the top row of tubes was removed and subsequently replaced by aluminium louvres. The opening of the louvres was fully adjustable.

4 — EXPERIMENTAL TECHNIQUE

In order to ascertain the practical effects of changes in the equipment design, it was necessary to measure the performance of the complete unit under each set of operating conditions. This assessment of performance was achieved either qualitatively by flow visualisation or quantitatively by measuring the velocity and pressure of the air within the fan ring and plenum chamber and the power consumed by the fan.

Flow visualisation tests were performed using a vapourised oil which could be injected at any point within the plenum chamber. Two series of tests were performed, each having a different objective. The first series was intended to give an overall picture of flow within the plenum chamber, and particularly, to study the recirculation in the corners of the plenum. The second series augmented Kiel probe [36] measurements and was used to establish the presence of downflow in the eye of the fan.

The measurement of velocity was made by means of a hot-wire anemometer. From the readings it was possible to obtain mean flow velocities [37, 38]. Total head measurements were made at the same points as the hot wire measurements again using a Kiel probe. The head of the probe was directed towards the plenum chamber base, but if the pressure reading indicated any likelihood of recirculating flow, the probe was rotated through 180 degrees, and a further reading taken. As previously mentioned the work was supported by flow visualisation tests to ascertain the direction of flow.

Direct measurements of fan power were achieved by connection of a precision grade 3 phase wattmeter across the output terminals of the fan motor switch. This instrument, which was chosen because of its relative accuracy and simplicity, gave separate direct readings of current, voltage and power factor. These separate readings enabled power consumption to be derived for each phase and comparison to be made with the direct meter reading.

5 — EXPERIMENTAL OBSERVATIONS

Initially the air flow distribution and corner recirculation were observed using the 4.375 fan with a 3 ft. high plenum and smooth tubes to provide the outlet resistance. The smoke injection experiments showed that there was a central core of rotating air which gradually expanded from the circular to square configuration. A transitional

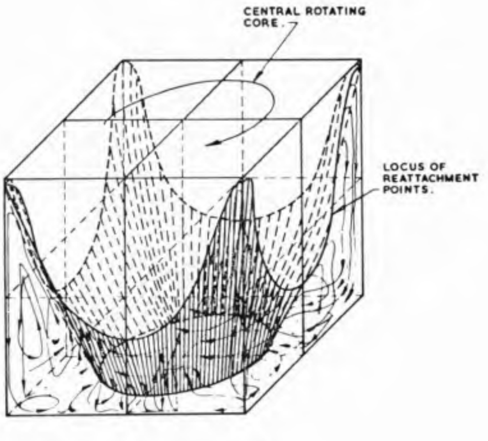


Fig. 3

outer layer existed which expanded to fill the square duct, reaching the sides of the plenum at varying distances from the inlet to the plenum chamber. These points produce the locus of re-attachment (fig. 3) below which the flow was observed to be highly complex and rather unstable with rotational flow, as well as downflow (flow towards the plenum base). This rotational flow occurred both in the direction of rotation of the fan and, close to the plenum wall, opposite to the direction of rotation.

5.1 — *RECIRCULATING FLOWS*

Following the first series of flow visualisation tests, quantitative measurements of flow velocity and pressure were made within the fan ring and plenum chamber, initially with fan 4.375, but for the most part with the 4.167 fan. From the total head measurements within the ring of the 4.167 fan, it was deduced that near the hub, downflow occurred — rotation of the total head probes through 180° caused an increase in the measured pressure. This downflow was observed to occur in varying amounts, depending on the geometry of the plenum chamber and the volumetric flow rate, and was additional to the downflow in the corners of the plenum. (Figure 4 is an example of the many results obtained.)

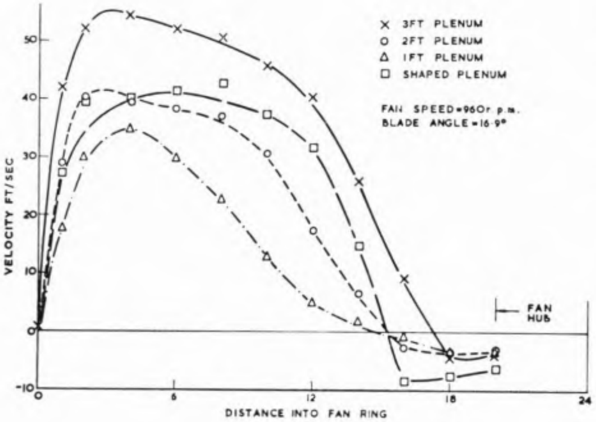


Fig. 4

5.2 — *RECIRCULATION IN THE EYE OF THE FAN*

Because of the high static pressure generated by fan 4.167, the amount of smoke which could be injected close to the eye of the fan was too small for photography, though visible to the naked eye. Flow visualisation near the centre of the fan was only possible for the 2 ft. high square plenum and the shaped plenum. From this limited series of tests it was possible to confirm the findings with the total head probes, and the radial position of transition from downflow to upflow in the fan ring. It was also observed that the distance penetrated vertically into the plenum by the area of recirculation is not more than 4 ins. except in the region directly above the fan hub where the flow was particularly unstable.

5.3 — *FAN PERFORMANCE*

In the design of an air-cooled heat exchanger, it is necessary to specify a desired flow-rate and fan static head. Selection is then generally based on predicted fan performance as given by the manufacturers' performance curves. Figs. 5, 6 and 7 show the manufacturers' curves for the 4.375 and 4.167 fans. Also shown in these figures are experimental data taken on the model air-cooled exchanger to compare with the predictions. From these it can be seen that the power consumption of the 4.167

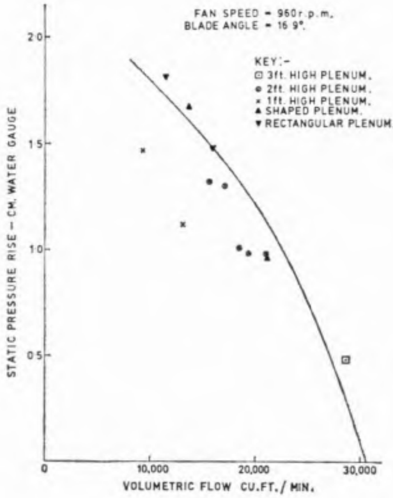


Fig. 5

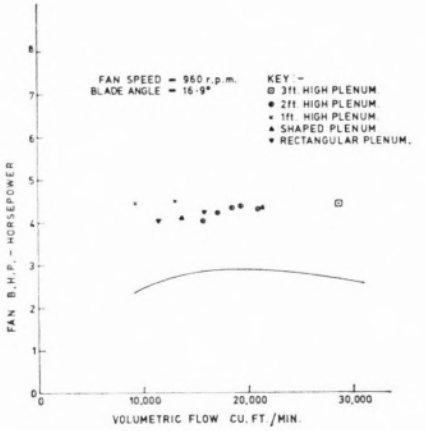


Fig. 6

fan is considerably greater than the manufacturer's data, thus giving a reduced fan efficiency. The static head values, except at low flow rates in non-square plena, are also below the fan curve. Fan 4.375 on the other hand, shows good agreement with the manufacturer's predictions for both power consumption and static head.

There is probably a number of factors associated with the fan design and the system in which the fan operates, which combine to produce these differences. A major reason for the efficiency of the 4.167 being less than that predicted from the fan manufacturer's curves probably lies in the flow distribution at inlet to the plenum.

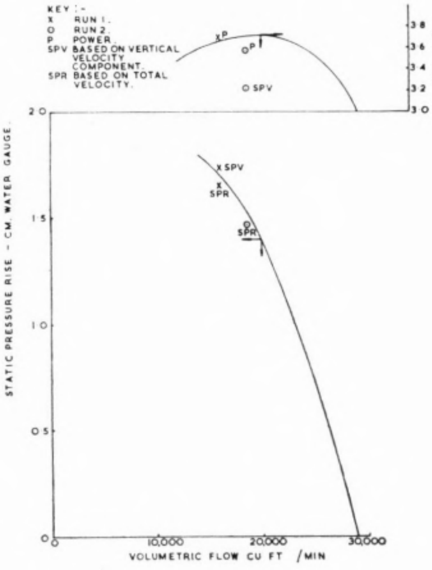


Fig. 7

Fig. 8 compares the distribution of vertical flow in the fan ring downstream of each fan, at approximately equal flow rates. From this figure it can be clearly seen that the velocity profile for fan 4.375 is more uniform than for the 4.167 fan. No recirculation is present in the fan ring of the 4.375, but occurs in the 4.167 fan ring. This recirculation inevitably leads to higher flows in that part of the flow annulus of the fan ring where upward flow occurs.

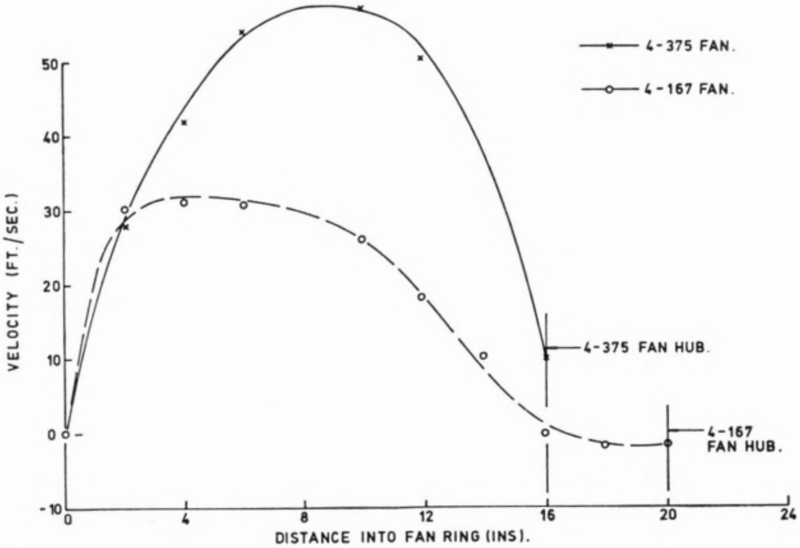
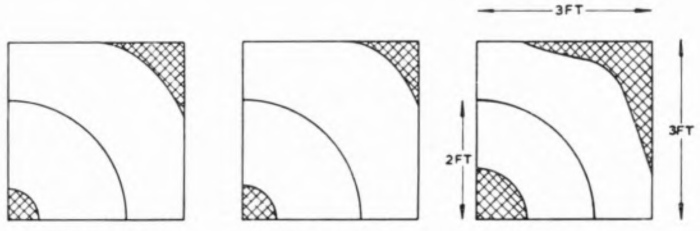


Fig. 8

6 — PLENUM CHAMBER DESIGN

The function of a plenum chamber is to effect the transition of a mass of air from the fan to the tube bundle. The inlet will be circular, the flow swirling and the velocity profile across the inlet, highly non uniform. The two extremes, very short and very long plena, provide either no flow over the majority of the tube bundle, or a more uniform flow but excessive friction loss through the plenum. In relation to the experimental results, these two extremes manifest themselves in the 1 ft. and 3 ft. high plena respectively.

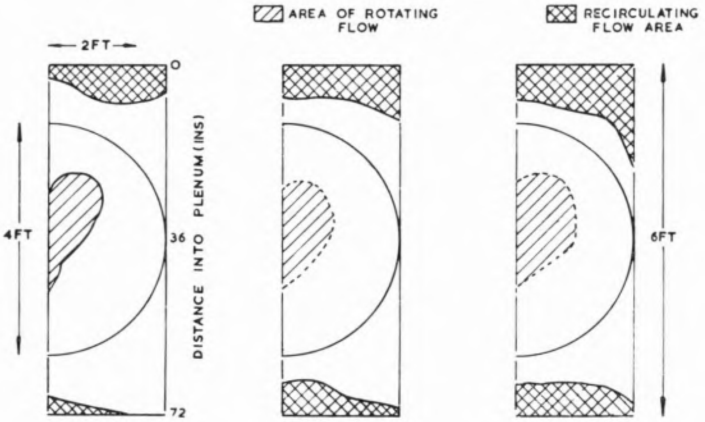


PLENUM HEIGHT = 3FT PLENUM HEIGHT = 2FT PLENUM HEIGHT = 1 FT

Fig. 9

For the 1 ft. high plenum there is very little redistribution of the fan ring flow profile and a large amount of recirculation in the plenum. In the case of the 3 ft. plenum, the flow pattern has been smoothed considerably, but at the expense of corner recirculation. The 2 ft. plenum is the best of the three heights tested, even though it suffers from recirculation both in the eye of the fan and in the corners (see fig. 9).

For the three plenum types studied, square, rectangular, and shaped, each 2 ft. high, the aspect ratios were 2.87, 1.91 and 2.87 respectively — where aspect ratio is defined as the cross-sectional area of the plenum divided by the cross-sectional area of the fan. In the rectangular plenum the recirculation, both in the eye of the fan and the corners, was large, and the flow redistribution was poor (see fig. 10). As might be expected, for the shaped plenum addition of the shaping to remove the corners of the plenum effectively removed downflow near the walls of the plenum chamber. Recirculation in the eye of the fan was increased but the redistribution of flow was less than for the 2 ft. square plenum, and more than for the 1 ft. case. Table 2 shows the results obtained for the square and shaped plena and from this it can be seen that addition of shaping improves the performance of the fan and plenum as a unit.



3 INS FROM INLET TO BUNDLE 12 INS FROM BASE 3 INS FROM BASE

Fig. 10

Table 2

Flow in square and shaped plenum chambers

	Square	Shaped
Fan speed (r. p. m.)	960	960
Blade angle (°)	16.9	16.9
Louvre angle (°)	47.5	47.5
Volumetric flow (ft³/min)	19300	21400
Static head (cm. water)	0.98	1.01
Power consumption (HP)	4.36	4.33
Fan efficiency (%)	25.9	30.3
Manufacturer's quoted efficiency (%)	53.7	50.8
% operating efficiency (%)	48.2	59.7
Static head at plenum inlet (cm. water)	0.94	0.96
Pressure drop across outlet (cm. water)	0.91	0.93
Static head change across plenum (cm. water)	— 0.03	— 0.03
Maximum deviation from mean flow velocity at tube outlet (%)	110	211
R.M.S. flow velocity at entry to fined tube bundle (%)	40.0	61.6

7 — DISCUSSION

Previously the two major effects examined, fan design and plenum design, were considered separately. This was done to clarify the results and simplify the presentation, but it is a major conclusion of this work that in order to achieve maximum efficiency from an air-cooled heat exchanger, the overall aerodynamic design is the important factor, and neither fan nor plenum chamber can be designed sucessfully in isolation from the other. It does not mean however, that comparisons of the individual parts of the exchanger are invalid, merely that they should point out the differences between the systems compared.

This need for comparison of like with like is particularly important when considering fan design. For the two fans examined, the only factors in common were diameter, speed of rotation, and drive. Because of this, the conclusions reached concerning fan performance must be considered in the light of the plenum chambers to which they were attached as well as the differing fan parameters, since the plenum chambers may have been more suited to one fan than the other.

Maximum aerodynamic efficiency will occur when the amount of air required for the specified cooling duty is at a minimum (this not only reduces the power required to blow the volume of air, but reduces the pressure drop across the tube bundle to a minimum). Theoretically this will be achieved with a uniform flow distribution over the outlet tube bundle, and so it is the duty of the plenum chamber to achieve as uniform a flow profile as possible at the inlet to the tube bundle. The two factors determining the degree of uniformity are the design of the plenum and the velocity distribution at inlet.

The experimental results have shown that the greater the degree of symmetry within the plenum, the better the flow distribution but that with plena which are excessively long or excessively short, performance is impaired by the presence of recirculating flow, both above the hub of the fan and in the corners of the plenum. It is in determining the effects of different plenum geometries on the degree of recirculation that flow visualisation is particularly useful. By injecting smoke at appropriate points where recirculation might be expected, a quick and reliable method is available to assess the significance of the particular change, and provide evidence upon which the decision whether or not further investigation of the given system is worthwhile.

Smoke injection was able to confirm that shaping the plenum resulted in elimination of corner recirculation (by eliminating the corners), but fan hub recirculation was found to have increased. This is one obvious example of the need to design an overall system. The corner recirculation is a direct consequence of the plenum geometry and the step change in flow area at inlet, but the fan hub recirculation is generated by the fan, and it thus might be expected that elimination of corner recirculation would have no effect on the fan hub recirculation.

Further examples of the interaction between the different design parameters are observed when considering the optimum height for the plenum. It was concluded that for a square plenum, 2 ft. was the best height but that the introduction of shaping increased the non-uniformity of the flow at the inlet to the tube bundle, effectively reducing the overall height to be equivalent to a $1\frac{1}{2}$ ft. high square plenum. The outlet resistance was also found to affect the optimum plenum height as raising the height from 2 ft. to 3 ft. resulted in an increase in corner recirculation, which was attributed to the reduction in the pressure gradient across the plenum chamber.

Another important feature of the investigation are the conclusions with respect to the specification of aspect ratio. A recent report [1] has advocated that for forced draught units at least 40 % of the tube area should be covered by the fan. For the square plenum the aspect ratio was 34 %, for the rectangular plenum it was 51 %. From the results the flow distribution to the tube bundle with the square plena of low aspect ratio was far better than for the rectangular plenum. This suggests that the specification of fan to tube area ratio should be given as a function of the plenum geometry.

One factor which is of major significance is that the downstream velocity profile produced by the fan showed little interaction with the plenum since it was found to be independant of plenum height and only slightly dependent on plenum shape. It was however, found to be directly dependent on fan speed, blade design, fan ring design and fan hub design. In respect of this velocity profile, the 4.375 fan was found to be superior in every case. It did not produce any recirculation above the hub and a smoother velocity profile. The 4.167 fan, with no dome above the smaller hub and much narrower blades at the root, was not capable of generating sufficient flow or head to overcome the downflow generated by the swirling plenum flow. It is not possible though to isolate which factor, the larger hub diameter, the wider fan blades, or the hemispherical dome blocking most of the recirculatory area of the 4.167 fan, prevents recirculating flow ocurring in the eye of the 4.375 fan.

The 4.375 fan was also found to give much better agreement with the manufacturer's performance data than the 4.167 fan. Since the plenum chambers were similar and the different outlet resistances considered to have little or no effect on the fan performance, it is concluded that the differences are probably due to the different fan designs. During flow measurements it was observed that the 4.167 fan, with a shallow fan ring and inlet cone, was far more susceptible to wind fluctuations and with wind speeds of force 3, measurements became difficult whereas the 4.375 fan with a deep fan ring appeared unaffected at higher wind speeds. It would thus appear that the 4.375 fan has a number of design advantages over the 4.167 fan, but it is also necessary to ensure that the fan chosen is capable of meeting the specificed head and volumetric flow values.

It is concluded that for the particular fan and plenum systems tested, design features such as a deep fan ring, uniformly shaped blades with a relatively large streamlined hub, increase the efficiency of the fan and the air-cooled exchanger.

Finally it is relevant to consider the application of results from the testwork presented here to large industrial units and the problems of scaling. From the theoretical viewpoint the flow through the fan and plenum chamber of the air-cooled heat exchanger may be described as three-dimensional swirling recirculating turbulent flow. Flow in each coordinate direction is described by one Navier-Stokes equation, and a further equation, the continuity equation, is employed [38]. These four equations describe the time dependent flow of a fluid and are insoluble analytically.

At the time of the present work the nearest case to the prediction of flow through an air-cooled heat exchanger was a computer program for the prediction of two-dimensional time independent swirling recirculating turbulent flows [39]. Predictions from this program were compared with experimental data obtained from the two-dimensional cylindrical plenum. Using a two equation turbulence model, this new program was able to produce predictions of the distribution of vertical velocity and swirl velocity within the plenum chamber, and these results are presented in figs. 11 and 12. It can be seen from these diagrams that the lower flow rate and swirl velocity give the better agreement between predicted and experimental values. The general shape of the predicted curves conforms with the experimental data over most of the plenum chamber, but differences occur, particularly near the axis of symmetry, and overall, agreement is best described as moderate.

This apparent disagreement is not however attributable solely to inaccuracies in the experimental data, but merely highlights the difficulties involved in the prediction of recirculating flows. Apart from the computational difficulties, the main problem lies with choice of turbulence model. The two equation model used (thus increasing the number of equations to be solved simultaneously to five) is seen to be inadequate for the present problem. This is not very surprising as it incorporates a number of empirical constants which were derived from boundary layer flows. Even more important however, is the inadequacy of the basic model which is derived on the basis that the turbulence is the same in each co-ordinate direction. For non-swirling low velocity uniform flows this assumption is reasonable, but, for the present conditions of large swirl and non-uniform inlet velocity, the shear stress and hence viscosity, in each co-ordinate direction is very unlikely to be equal, and the assumption becomes unreliable.

It is thus seen that the prediction of complex flows such as those in an air-cooled heat exchanger is still far away from being reliable, accurate, and readily available. The problems to be overcome are both computational and theoretical, and until significant advances can be made in both fields it appears that experimentation still has a large part to play in deciding what is best for the design of an air-cooled heat exchanger.

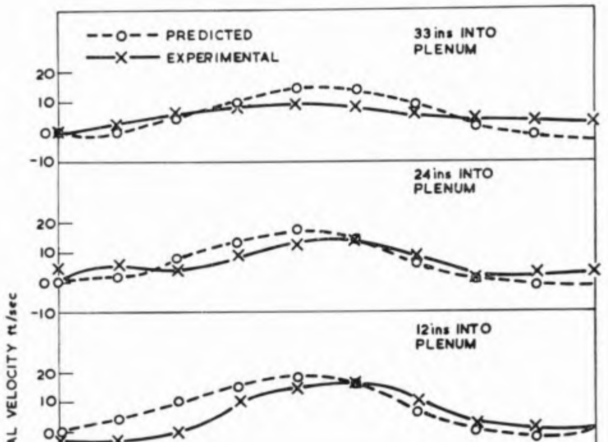


Fig. 11

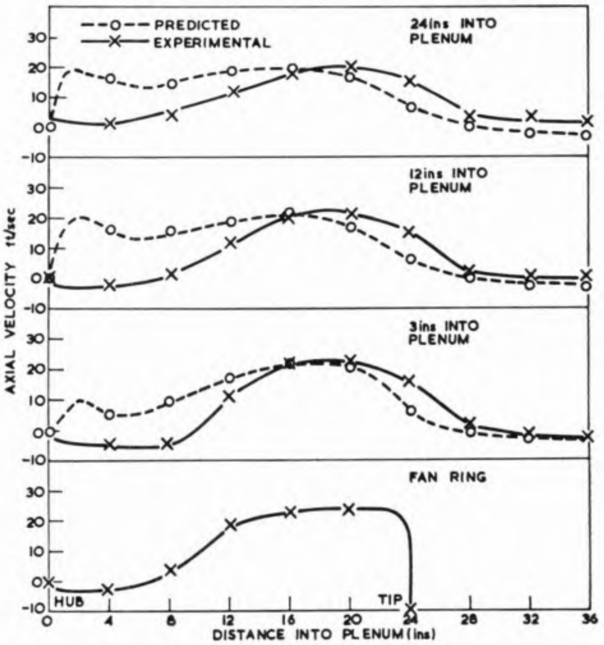


Fig. 12

While it is recognised that any results obtained are not necessarily generally applicable to full size units, the nature of the flow indicates that, in most cases, scaling will not be unduly difficult. This is because the flow is almost completely turbulent, with the wall boundary layer thickness small in relation to the geometrical size of even the model unit tested. The effect of increasing the physical size will normally be negligible on the boundary layer thickness, and in the present circumstances the effect on the overall flow will also be negligible. Any effects observed during experimental tests on the model air-cooled heat exchanger are thus likely to be equally valid for a full size unit.

8 — CONCLUSION

To achieve efficient designs of forced draught air-cooled heat exchangers it is concluded that the overall system design is extremely important. For the particular fan and plenum systems tested design features such as a deep fan ring, uniformly shaped fan blades with a relatively large streamlined hub increase the efficiency of the fan and the air-cooled heat exchanger.

Results indicate that the use of a square box plenum gives more satisfactory air-flow distribution than for a rectangular box plenum of the same height. The optimum height of a square plenum is about equal to half the fan diameter. Shaping of the plenum helps to minimise flow recirculation but the depth of plenum requires to be greater than that for a square plenum to obtain an equally good airflow distribution to the finned tube bundle. The better fan to bundle aspect ratio is suggested to be a function of the plenum geometry.

A computer program for 2-dimensional, swirling, time independent turbulent flow was used to predict the flow characteristics in a cylindrical plenum. Experimental measurements using a two equation turbulence model were in reasonable agreement with predictions. This is encouraging indicating that with further development theoretical flow models may eventually be used to predict the air-flow characteristics of large air-cooled heat exchangers.

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RESUMO

Estudaram-se as características de escoamento de um modelo de permutador de calor arrefecido a ar usando técnicas de visualização do escoamento e medições por meio de anemómetro de fio aquecido e sonda de Kiel.

Os resultados obtidos utilizando câmaras de «plenum» tipo caixa mostram a existência de um núcleo central de ar em rotação com áreas apreciáveis de recirculação abaixo dos pontos de reentrosamento, em especial junto aos cantos. Configurações da ventoinha de baixa razão eixo/extremidade originaram um retroescoamento significativo junto ao eixo. A recirculação junto aos cantos desaparece com o uso de um «plenum» perfilado. No sistema ensaiado, aspectos construcionais tais como a profundidade do anel da ventoinha, perfilação uniforme das pás da ventoinha com um eixo relativamente grande e estriado conduziram a um aumento da eficiência da ventoinha e permutador.

Conclui-se que, comparativamente, um «plenum» quadrado é preferível a um «plenum» rectangular. Para o «plenum» quadrado a altura óptima parece ser cerca de metade do diâmetro da ventoinha para unidades de alimentação dirigida. Prevê-se para o futuro a possibilidade de estimar por computador as características de escoamento de permutadores de calor arrefecidos a ar de grande dimensão.

J. J. B. ROMERO

Universidade do Minho
Braga — Portugal

JOÃO DE DEUS R. S. PINHEIRO

Chemical Engineering Department
Birmingham University — U. K.

THE APPLICATION OF LIQUID THERMAL DIFFUSION AS A SEPARATION TECHNIQUE (1)

The separation of liquid mixtures by thermal diffusion has been regarded as uneconomical in comparison with other more conventional separation processes due to the high energy costs predicted by the available design equations. As a result, the applications of the technique have been essentially limited to laboratory operations as an analytical-tool or in preparative-scale purifications. However, earlier analysis on the applications of the technique have not taken into acount the very special characteristics of the thermal diffusion process, namely, the possibility of utilizing virtually any temperature gradient at any temperature level. Yet, this unique feature may be the key factor in determining the economic viability of industrial applications.

In the present work, the principal aspects concerned with the application of liquid thermal diffusion as a separation technique are examined for both batch and continuous operations and a new, semi-batch, type of operation is suggested. The available design methods are also discussed and a new approach for the design of continuous columns is proposed.

1 — INTRODUCTION

The application of liquid thermal diffusion as a separation technique has been mostly limited to small-scale operations where the output and heat requirements are not restrictive factors. In these cases, thermal diffusion columns have been used either as an analytical tool or in preparative-scale separations which cannot be accomplished by other more conventional methods [1-3]. In general, these operations are batchwise and the parameters to optimize are the degree of separation attainable and the time of operation.

In large-scale applications, however, besides the technical aspects it is necessary to estimate the economical viability of the process.

Several pilot-plant studies and earlier industrial plants [4, 5] have demonstrated that large-scale continuous units do not pose any significant technical problem: they are easy to operate, almost trouble-free and the performance may be satisfactorily predicted by the phenomenological theory of the process or from small-scale experiments. Notwithstanding, industrial applications have failed to appear and the reasons must lie on the high energy costs predicted by current design methods which are based on the work of KRASNY-ERGEN [6] on the later 40's.

2 — THE FOUNDATIONS OF THE DESIGN

In small-scale operation the design of the equipment and the selection of the operating conditions are dictated solely by the technical aspects and therefore in most cases they are based on the phenomenological

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(1) Presented at CHEMPOR' 75 held in Lisbon, 7-12 September 1975 at the Calouste Gulbenkian Foundation Center.

Papers presented at this International Chemical Engineering Conference can be purchased directly from Revista Portuguesa de Química (Instituto Superior Técnico, Lisboa 1, Portugal) at the following prices per volume sent by surface mail, postage included (in Portuguese Escudos):

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This paper was presented at the Transport processes section equations of the batch column, in accordance with the particular objectives desired.

In the case of industrial (large scale) operations, however, it is necessary to optimize the column dimensions and the operating conditions in order to obtain the most economical solution. This is the aim of the earlier work of KRASNY-ERGEN [6] and BENEDICT [7] and the more recent and simplified formulation of POWERS [8].

These authors considered two aspects of the problem:

1) The selection of the operating wall temperatures to minimize the heat transfer area and the heat input, and
2) The determination of the column dimensions that minimize the cost-function Π defined by

$$\Pi = \left[S + \frac{p}{2\omega} \right] \int dA \tag{1}$$

where S is the amount of fixed costs per unit of column area and (p/2ω) is the power cost per unit of area and unit of time.

The first objective implies some recommendations which, in fact, tend to overload the power costs since the minimum amount of surface is secured by working with the greatest possible temperature difference between the hot and cold walls and the minimum heat input is secured by using an absolute hot wall temperature two to three times the absolute cold wall temperature. In practice, then, the hot wall must be of the order of 350 °C or more if tap water is used for cooling. But, this means that the process is virtually uncompetitive at those temperature levels due to its low thermodynamic efficiency [9] in comparison with other less energy-demanding separation techniques.

With regard to the determination of the most economical column dimensions for a given value of ΔT — the second aspect of the design under consideration — it is of importance to analyse the cost-function Π, namely in what respects the association of the power costs with the term (p/2ω). The suggestion is that the power is consumed in producing the temperature gradient which is a slightly different way of putting the question. Assuming further that the power costs are directly proportional to the gradient attained through the constant a, it is possible to write

$$\text{Power cost} = a \cdot \frac{\partial T}{\partial x} = a \, \frac{\Delta T}{2\omega} \tag{2}$$

Noting that, in this aspect of the design, ΔT is pre-fixed, the product (a.ΔT) is constant (represented by p). Hence

$$\text{Power cost} = \frac{a \cdot \Delta T}{2\omega} = \frac{p}{2\omega} \tag{3}$$

The conclusion expressed by equation (3) is not, however acceptable. In fact, the power costs are intrinsically associated with the heating and cooling of the column walls which is to say with ΔT. If, as in the present circumstances, the value of ΔT is fixed, then the power costs become inevocably determined whatever the values of (2ω) or ($\partial T/\partial x$) may be. In other words, when the value of ΔT is fixed, the changes in the value of (2ω) do not affect the power-costs but solely the performance of the column as predicted by the appropriate phenomenological equations.

The discrepancy between the implications of equation (3) and the reality is, indeed, a consequence of this other discrepancy: having first assumed — in establishing equation (2) — that the temperature gradient was the design variable, the subsequent developments and analysis are carried out in terms of other variables, in this case, ΔT and (2ω).

It may then be concluded that the validity of the current design methods is, at least, doubtful and, an important «corolarium» is that the comparisons that have been made in the literature between thermal diffusion and other separation techniques [7, 10] are impaired by the use of the above equations to predict thermal diffusion costs.

But, the existing assessments on the industrial viability of thermal diffusion as a separation technique become even more questionable when realizing that, probably the most important features of the technique have been systematically forgotten. Indeed, it is quite surprising that no mention has been made to the capability of the process to separate mixtures at any temperature level and under any temperature gradient, the only factor affected being the time of operation or the ratio (σ/B) but *not* the separation attainable. If, thus, instead of creating new powerful heat sources for use in thermal diffusion, cheap heat sources available are used without incurring in any significant extra-cost, then the process may work at virtually zero running costs and only the capital for the equipment is involved. Even the manpower required is practically negligible.

In referring to 'cheap heat sources available' it is meant 'non-used' heat sources like the solar energy for which simple devices of capturing the necessary heat may be arranged using existing methods [11] as shown in fig. 1. (Other «non-used» sources are, for instance, the geothermal energy where it occurs, or even the existing temperature gradient between the inside and outside of industrial and other buildings.) More frequently however, the available heat source is to be provided by other operations of heat transfer already existing in the industrial plant. In fact, the thermal diffusion column may be considered as an heat exchanger — see fig. 3 — and therefore it may be enclosed on the flow-circuits in parallel with existing heat exchangers, the net power consumption being in these circumstances much less than predicted by the design equations. An example where thermal diffusion could be used «on line» is the manufacture of ethanol by hydrogenation of ethylene whose flowsheet shown in fig. 2 indicates two possible locations of a thermal diffusion unit (in parallel with the cooler or the heater) to perform the purification of a fraction of the crude ethanol — see fig. 3.

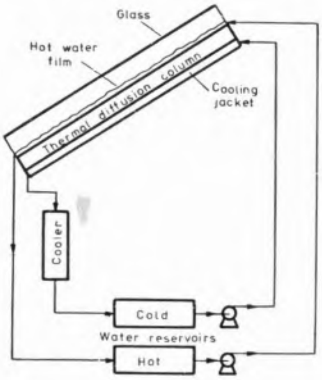

Fig. 1
A means of using solar energy for heating a thermal diffusion column

Summarizing this section it may be said that:

1) Contrary to what has been currently accepted, the separation by thermal diffusion may be economically interesting.

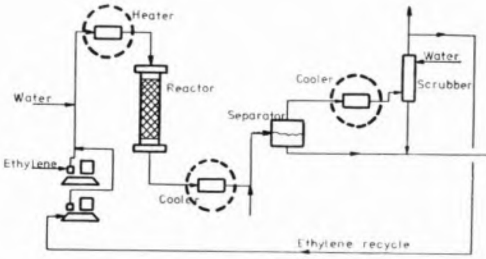

Fig. 2
Ethanol synthesis flowsheet with the circles showing the possible locations of a thermal diffusion unit

2) The approach for establishing a design procedure appears to be, now, substantially different from that of Krasny-Ergen [6] and Benedict [7]. In brief, the new premisses for design are:

   a) The value of ΔT is fixed by external conditions, namely, the heat source available.
   b) The operation costs are essentially related to the equipment and maintenance costs.

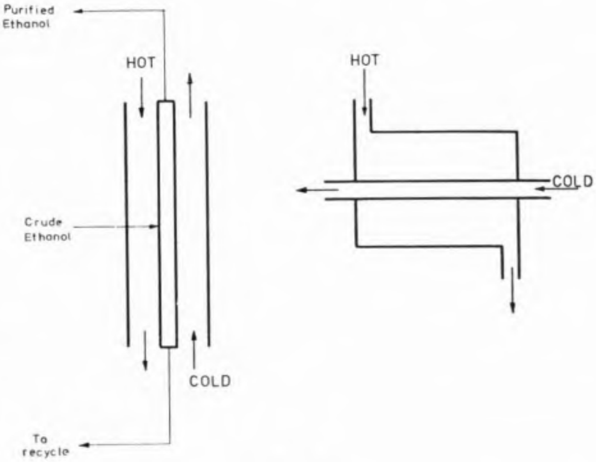

Fig. 3
The analogy between a thermal diffusion column and an heat exchanger (ex. purification of crude ethanol)

3 — BATCH SEPARATION

3.1 — *EQUATIONS*

The batch separation of a binary mixture in a thermal diffusion column shows an evolution with the time of the type represented in fig. 4 where Δ_∞ is the equilibrium separation, assimptotically reached, and t_r is the relaxation-time which, for the time being, may be defined as the time required to attain about 70 % of the steady-state separation.

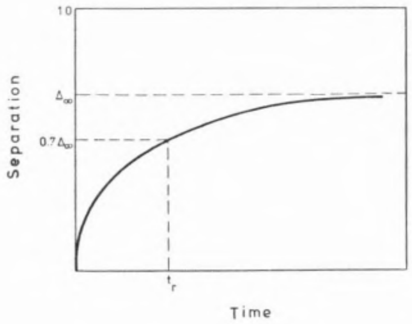

Fig. 4
The separation vs. time curve in batch operation

There are two regions of the separation curve of fig. 4 that may be expressed through simple equations derived from the phenomenological theory of the thermal diffusion column. The first is in the short time range such that

$$t \leq \frac{(2\omega)^2 T_{av}^2}{14\alpha^2(\Delta T)^2 D} \mid \lambda \mid^{1.82} \tag{4}$$

for which Ruppel and Coull [12] obtained

$$(\Delta)_{RC} = \frac{4c_o(1-c_o)(\Delta T)\alpha}{45 T_{av}(2\omega)} \sqrt{\frac{2835D}{2\pi}} \sqrt{t} \tag{5}$$

The other equation is for times

$$t \geq 0.3 t_r \tag{6}$$

and was derived by Hoffman and Emery [13]:

$$\Delta = \Delta_\infty\left(1 - k_3\, e^{-t/t_r}\right) \tag{7}$$

where k_3 is a coefficient that may generally be regarded as a constant and equal to $8/\pi^2$ with an error less than 1 %, and the exact values of Δ_∞ and t_r are given by the following equations:

$$\Delta_\infty = \frac{(e^{c_o\lambda} - 1)(e^{\lambda} - e^{c_o\lambda})}{e^{c_o\lambda}(e^{\lambda} - 1)} \tag{8}$$

$$t_r = \frac{10}{7}\ \frac{T_{av}^2(2\omega)^2}{\alpha^2(\Delta T)^2 D}\ \frac{1}{\frac{1}{4} + \frac{\pi^2}{\lambda^2}} \tag{9}$$

and λ, the dimensionless length of the column is

$$\lambda = \frac{504\alpha D\eta L}{\beta g T_{av}(2\omega)^4} \tag{10}$$

In the case of small separations and moderately concentrated solutions for which the product [c(1-c)] may be taken as constant, Powers [14] obtained a more simple solution for the parameters Δ_∞ and t_r in equation (7):

$$\Delta_\infty = [c(1-c)]\cdot\lambda \simeq 0.25\lambda \tag{11}$$

$$t_r = \frac{9!D\eta^2L^2}{\pi^2\beta^2g^2(\Delta T)^2(2\omega)^6} \tag{12}$$

3.2 — *APPLICATION OF THE «IDEAL» EQUATIONS TO «PRACTICAL» SEPARATIONS*

The preceding equations are derived from the phenomenological theory of Furry *et al.* [15] which involves several simplifying assumptions. The validity of these assumptions and of the theory has been fully discussed recently by Horne and Bearman [16] and Romero [17, 18] and the conclusion is that they are essentially acceptable except in what concerns the constancy of the distance between the walls. Indeed, ROMERO and BOTT [19] confirmed earlier suggestions [13, 20] that small eccentricities in the annular space do affect the performance of a thermal diffusion column and, as a result the phenomenological equations derived for an «ideal» (perfect) column were unable to describe the actual column. To overcome the difficulty Bott and Romero introduced the 'equivalent annulus width' concept — the annulus width of a perfect column that gives the same separation as the actual imperfect column, the other variables being kept constant — based on the analysis of the hydrodynamics of annular spaces and on the influence of the flow pattern on separation in thermogravitational columns.

In practice, the introduction of the 'equivalent annulus width' means that the value of the wall spacing to be used in the phenomenological equations, (2ω), is not the same as the mechanically measured distance $(r_2 - r_1)$, but rather

$$2\omega = (r_2 - r_1)\cdot\nu \qquad (13)$$

with $\nu \geq 1$.

The determination of ν, which is constant for a given column was presented in a recent paper by ROMERO and PINHEIRO [21] where the experimental evidence of the validity of the concept in correlating experimental data is also shown.

As a result of the introduction of ν, the separation equations maintain their functional dependences on the variables predicted by the phenomenological theory but, in fact, a new variable, ν — the deviation from geometric ideality —, must be considered along with the distance $(r_2 - r_1)$ when discussing the effect of (2ω) on separation.

Besides allowing for the correlation of experimental data in terms of the phenomenological equations, the equivalent annulus width concept is of great utility in design since it enables the definition of a degree of imperfection of the column which may be evaluated by calibrating it with a «standard» mixture and determining ν. On the other hand, it is likely that low values of $(r_2 - r_1)$ will yield the larger values of ν, loosing therefore the eventual benefits of a small wall distance [as shown by equation (13)].

3.3 — *THERMAL DIFFUSION*

3.3.1 — THERMOGRAVITATIONAL COLUMNS

The two most popular and simple columns are the parallel plate column and the concentric cylinder column. The later has the advantages of making the heating and cooling of the walls more simple and requiring less space. The parallel plate column is more flexible from the point of view of changing the wall distance. It also enables the column to be operated with an inclination from the vertical or with a packed annular space.

The purpose of inclining the column or using the packing is to deflect the particles streamlines thus reducing the convective flow and the remixing associated with it. The separation attainable at the equilibrium is enhanced in both the inclined and packed columns as compared to the conventional apparatus, but the time of operation required is also greately increased, and therefore the gain is not much.

The equations describing the inclined column may be obtained from the conventional column equations by substituting the gravity field component g by g cos θ where θ is the deflection angle from vertical. The optimum angle of inclination is evaluated by setting $(\partial\Delta/\partial\theta) = 0$ and solving for θ. This column was studied by POWERS [22] and CHUEH and YEH [23] who were able to confirm the theory experimentally.

A phenomenological theory for the packed column has been proposed by LORENZ and EMERY [24] but the experimental data has not always agreed with the theory [24, 25]. This, however may be due, in part, to the difficulties in handling the packing in the very narrow gap which results in poor reproductibility in the experimental conditions. Other types of columns make use of barriers [26] or a wire wrapped along the inner cylinder of a concentric apparatus [27] but, besides its intrinsic complexity of construction they do not show any real improvement relatively to the other types mentioned.

3.3.2 — NON-THERMOGRAVITATIONAL COLUMNS

Since the transport process in a thermal diffusion column results from the combination of the demixing in the horizontal direction with the vertical convection it is conceivable that other driving-forces than the thermal gradient have been used to promote the transport in either the horizontal or vertical direction. VON HALLE [28], for instance, used a column where the convection is obtained with an external reflux; BEAMS [29] and RAMSER [30] suggested the use of moving walls (in opposite direction) to obtain a Couette flow in the annular gap. More recently POWERS *et al.* [31] used an electrical field in the horizontal direction together with the thermal convection. In some cases, these apparatus may produce better separations than the thermogravitational ones but in most cases this is not so. Noting, furthermore, that these columns are not easy to operate its use in practice is not usually recommended.

3.3.3 — ROTARY COLUMN

This type of apparatus, first used by SULLIVAN *et al.* [32] only recently has received the attention of the investigators in the field [32-36]. Its hydrodynamics are rather more complex than those of the conventional static column due to the 3-dimensional flow pattern inside the annular space.

The experimental reports so far published appeared to be in poor agreement, but, quite recently, a phenomenological theory has been presented that not only explains the experimental data published but also indicates the variables that govern the performance of such a column, for speeds of rotation $\geqslant 10$ RPM.

Using the same basic arguments presented by BOTT and ROMERO [19] to introduce the equivalent annulus width concept, BOTT and PINHEIRO [37] defined a correction factor, Φ, that is a function of the factor ν previously referred and the speed of rotation, N.

The actual parameters to use in the Hoffman and Emery-type equation are (the astherisc means rotary)

$$\lambda^* = \frac{1.43}{\Phi}\,\lambda \tag{14}$$

$$t_r^* = t_r \cdot \frac{21}{25}\,\Phi\,\frac{0.25 + \pi^2/\lambda^2}{0.25 + \pi^2/\lambda^2(\Phi/1.43)^2} \tag{15}$$

For the short time range an equation similar to the Ruppel and Coull's is also written as

$$\Delta_{RC}^* = \Delta_{RC}\left(\frac{1.2}{\Phi}\right)^{\frac{1}{2}} \tag{16}$$

In all equations,

$$\Phi = \Phi(\nu\,,\,N) \tag{17}$$

and

$$\Phi \geq 1 \tag{18}$$

In fig. 5, the effect of parameters ν and N upon Φ is shown.

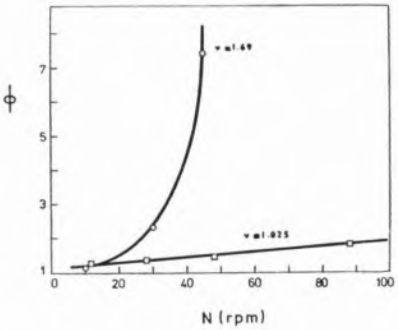

Fig. 5

The influence of the factor ν *and speed of rotation, N, on the value of the factor* Φ *(37)*

The above equations correlated earlier experimental data of ROMERO [33] and PINHEIRO [36] very satisfactorily and the parameter Φ — which in fact determines the actual improvement (or not) relatively to the static column — proved to be quite adequate to describe the column behaviour.

Briefly, it may be said that if the column is not too imperfect the separation is improved by rotation, the maximum being dependent on the mixture properties and on the value of Φ [37].

3.4 — *BATCH OPERATION DESIGN*

The characteristics of the apparatus and the selection of the experimental conditions are, naturally, dependent on the purpose of the operation. As mentioned before, the batch separation is generally associated with small-scale operations where the thermal diffusion technique is used as an analytical tool or as a preparative-scale process. In both cases, however, the emphasis is on the separation attainable and the time it requires. Other characteristics like the ease of operation and control and the flexibility to work with different types of systems at different temperatures, are also desirable.

As a first approximation, equations (10) and (11) may be used to conclude that the maximization of Δ implies the increase of the ratio $[L/(2\omega)^4]$, that is, of λ. But, since that ratio involves the 4th power of (2ω) the best way of increasing it is by decreasing the value of (2ω) which, according to equation (13) implies the decrease of the distance between the walls $(r_2 - r_1)$, and/or a decrease in the «imperfection factor» ν. This factor is likely to increase with the increase of the ratio $(L/2\omega)$ and if its value is to be kept close to unity one must expect an heavier burden on the construction costs. As a guideline from the experience and from the analysis of published data it may be recommended that the value of $(r_2 - r_1)$ should not be lower than about 0.04 cm if the column height does not exceed about 2 m. In practice this will yeld, on average, a value for the equivalent annulus width, 2ω, of the order of $0.05 - 0.07$ cm. For smaller values of L the value of 2ω will tend to be 0.04 cm.

This «lower limit» of (2ω) is also advisable in terms of the time required for the separation. In fact (noting that for these range of values of the annulus width equations (9) and (12) are identical) equation (12) shows how strongly the value of the relaxation time is affected by (2ω).

In what concerns the heating and cooling of the column walls it is recommended that, whenever the range of temperatures allows it, circulating fluids should be used preferably to electrical wires wrapped along the walls, since the former offers a much better homogeinity [38] and thermal irregularities are likely to increase the value of ν [20].

It is also recommended that the design should allow for several sampling parts along the column length not only to obtain different fractions in multicomponent mixtures but also to allow for the semi-batch operation to be carried out.

3.5 — *SEMI-BATCH OPERATION*

In many cases the separation vs. time curve has a high inclination in the short experimental times and then flattens out in a very short period as shown in fig. 6. In these situations only the time t_1 is required to reach a degree of separation close to Δ_∞.

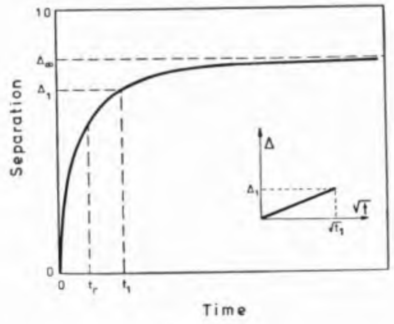

Fig. 6
The separation vs. time curve for small values of the relaxation-time

In general, the times t_1 are within the range where the Ruppel and Coull equation applies and it is seen, from equation (5) that in this period the column length is not an important variable, i.e. it is possible to use a relatively short column with a smaller value of (2ω). The operating variables in this case are the temperature difference, ΔT, and the annulus width, 2ω, or more precisely the ratio $(\Delta T/2\omega)$. It is seen that now, the value of (2ω) is not so decisive as in the batch operation — equations (10) and (11) — where it is elevated to the 4th power, and also that the value of (ΔT) may be manipulated in order to increase the separation in the time t_1.

It is thus possible to withdraw, at the time t_1, the top and bottom fractions each of which has on average a difference of about $(\Delta 1/2)$ from the initial concentration. The volume withdrawn is then replaced with fresh mixture and new top and bottom fractions withdrawn and now after a time $t_2 < t_1$ (since the process was already initiated) and with the composition of the fractions equal to those for $t = t_1$.

It is possible in this manner to obtain relatively large amounts of purified products with a composition of $(c_o \pm \Delta 1/2)$ in a relatively short period of time.

The operation may be taken further if the column is loaded with purified fractions. This is shown in fig. 7 where Δ_t and Δ_b are the separations obtained in the «top-fractions» and «bottom-fractions» columns, respectively. At the end, then the purified top and bottom products have compositions of, respectively

$$c_t = c_o + \frac{(\Delta_1 + \Delta_t)}{2} \tag{19}$$

and

$$c_b = c_o - \left(\frac{\Delta_1 + \Delta_b}{2} \right) \tag{20}$$

If a series of 3 columns is used it is also possible to conceive a «reflux» which carries material whose composition differs from the fresh feed, c_o, and therefore enter the column at different points.

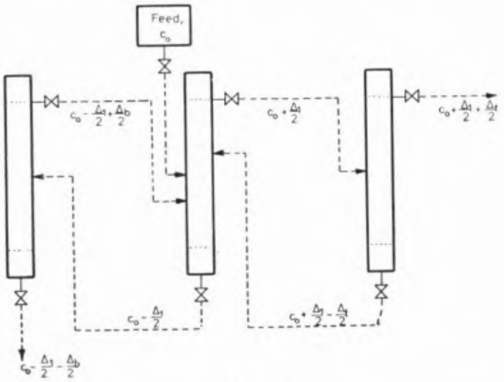

Fig. 7
3-column semi-batch operation

The semi-batch operation is, in fact, a bridge between the small-scale batch operation and the large-scale continuous process. Its use in the laboratory preparative-scale is however fully justified by the difficulties encountered in running the small-scale equipment continuously, due mainly to the extremely low product flow-rates that are imposed by the separation required (usually high) and the apparatus dimensions.

4 — CONTINUOUS SEPARATION

4.1 — *EQUATIONS*

The discussions on this operation shall be restricted to the case where the product $[c\,(1 - c)]$ may be taken as constant, i.e. where the initial feed concentration is not far from equimolarity and the degree of separation less than about 50 %.

It is also considered, according to the work of Powers and Wilke [39] that the process occurring in the upper section of the column (enriching section, subscript «e») are symmetrical to those of the lower section (stripping section, subscript «s») regardless of the location of the feed. This means that it is possible to discuss only one half of the column with a length L/2 and a product flow rate σ_{av} such that

$$\sigma_{av} = \frac{(\sigma_e + \sigma_s)/2}{\sigma_e \cdot \sigma_s} \tag{21}$$

The separation equation for the continuous thermal diffusion column was first derived by Furry *et al.* [15, 40] as an extension of the batch theory. Later, Powers and Wilke [22] and Emery [41] suggested some modifications to take into account the variation of the vertical concentration gradient with the horizontal distance. However, for the usual range of product flow-rates involved both the Powers and Wilke and Emery approaches reduces to the classical equation of Furry *et al.* [40].

$$\Delta = \frac{2c(1 - c)H}{\sigma_{av}} \left[1 - \exp\left(- \frac{\sigma_{av} \cdot L}{2K} \right) \right] \tag{22}$$

where H and K are transport coefficients given by

$$H = \frac{\alpha\beta\rho g B(\Delta T)^2 (2\omega)^3}{6!\,T_{av}\eta} \tag{23}$$

$$K = \frac{\beta^2 \rho g^2 B(\Delta T)^2 (2\omega)^7}{9!\,D\eta^2} \tag{24}$$

As discussed earlier, the eccentricity of the annular space decreases the deparation and increases the relaxation time of the batch separation. Considering that the batch operation is the limiting case of the continuous process when $\sigma = 0$, it appears that the «equivalent annulus width» concept must also be introduced in the case of continuous columns. Yet, it is also apparent that as the natural convection becomes less important, i.e. when the product flow rate increases, the influence of the factor ν (associated with the natural convection) becomes less significant and, in the limit when the flow in the enriching section is solely upwards (and in the stripping section, downwards) the influence of ν is null (for this case also $\Delta = 0$).

From the velocity profile in a continuous column

$$v_z = \frac{\beta g(\Delta T)\omega^2}{12\eta} [\xi - \xi^3 + r(1 - \xi^2)] \tag{25}$$

where ξ the dimensionless horizontal distance is

$$\xi = x/\omega \tag{26}$$

and r, the «relative product rate» is

$$r = \frac{9\sigma_{av}\eta}{\beta\rho g B(\Delta T)\omega^3} \tag{27}$$

it is seen that the limits of the continuous operation are defined by r which, in fact, is a measure of the relative importance of the forced flow:

$$r = 0 \ , \ v_z = (v_z)_{batch} \ , \ \Delta = (\Delta)_{batch} \ , \ \nu = (\nu)_{batch} \tag{28}$$

$$r = 1 \ , \ (v_z)_e \gtrless 0 \ , \ (v_z)_s \lessgtr 0 \ , \ \Delta = 0 \ , \ \nu = 0 \tag{29}$$

Assuming that the value of ν varies linearly with r it is then possible to write, for a continuous column

$$\nu = (\nu)_{batch}(1 - r) + r \tag{30}$$

Considering then, that $2\omega = (r_2 - r_1)$ and using ν explicitly, the separation equation becomes

$$\Delta = \frac{2c(1 - c)H}{\sigma_{av}} \nu^3 \left[1 - \exp\left(- \frac{\sigma_{av}L}{2K} \cdot \frac{1}{\nu^7} \right) \right] \tag{31}$$

and it may be shown that it represents the experimental data of POWERS and WILKE [22] better than the classical solution (without using ν).

In practice, the operation will in general be conducted in the small flow-rates region where the value of Δ remains sufficiently high to be interesting. In this case, the exponential in equation (31) may be expanded in a series whose terms beyond the third may be neglected.

Thus, for

$$\frac{\sigma_{av}L}{2K\nu^7} < 0.5 \tag{32}$$

equation (31) may be simply written, with an error less than 2 %, as

$$\Delta = c(1 - c) \cdot \frac{HL}{K} \ \frac{1}{\nu^4} \left(1 - \frac{\sigma_{av}L}{4K\nu^7} \right) \tag{33}$$

or, in terms of the steady-state batch separation, Δ_∞

$$\Delta = \Delta_\infty \left(1 - \frac{\sigma_{av}L}{4K\nu^7} \right) \tag{34}$$

4.2 — *DESIGN EQUATIONS*

It is of convenience to write equation (33) in a slightly different form to emphasise the dependences on the operating (design) variables:

$$\Delta = a_1 \frac{L_m}{(2\omega\nu)^4} \left[1 - \frac{\sigma_m L_m}{a_2 B_m (2\omega\nu)^7} \right] \tag{35}$$

$$a_1 = \frac{504\alpha D\eta}{4\beta g T_{av}} \cdot 10^2 \tag{36}$$

$$a_2 = \frac{4\beta^2\rho g^2}{9!D\nu^2} (\Delta T)^2 \cdot 60 \tag{37}$$

$$2\omega = r_2 - r_1 \tag{38}$$

and L_m and B_m are the column length and the column width in meters and σ_m is the mean product flow rate in g/min.

It is thus seen that both T_{av} and (ΔT) are not considered design variables since, according to section 2, these are fixed by the cheap heat sources available.

It is now possible to obtain the value of (2ω) that maximizes the separation in terms of the other design variables by setting $[\partial\Delta/\partial(2\omega\nu) = 0]$. This yelds

$$(2\omega\nu)_{opt} = \left(\frac{11}{4a_2}\right)^{1/7} \cdot \left(\frac{\sigma_m L_m}{B_m}\right)^{1/7} \tag{39}$$

Using this value in equation (35) and making

$$a_3 = \frac{7a_1}{11}\left(\frac{4a_2}{11}\right)^{4/7} \tag{40}$$

the following equation is obtained

$$\Delta_{max} = a_3 L_m^{3/7}\left(\frac{B_m}{\sigma_m}\right)^{4/7} \tag{41}$$

which gives the relations between the variables that yield the maximum separation.

If the degree of separation required, $\Delta^{\#}$, is prefixed then it is possible to write

$$\frac{\sigma_m}{B_m} = \left(\frac{a_3}{\Delta^{\#}}\right)^{7/4} L_m^{3/4} \tag{42}$$

and, substituting this value into equation (39) it is obtained, after rearranging

$$\frac{L_m}{(2\omega\nu)_{opt}} = \frac{\Delta^{\#}}{7a_1/11} \tag{43}$$

which emphasises the interdependence between the values of L_m and $(2\omega\nu)$ for optimum conditions. Similarly, equation (42) shows how the values of σ_m and B_m are strongly related.

Equations (42) and (43) are, in fact, those that govern the basic dimension of the equipment, together with the limits to (2ω), L_m and B_m dictated by the construction costs and by the values of the parameters a_1 and a_2.

When the degree of separation and the product flow rate are both pre-fixed at values of $\Delta^{\#}$ and $\sigma^{\#}$ it is possible to write equation (42) as

$$(\sigma^{\#})^{4/7} \cdot \Delta^{\#} = a_3 L_m^{3/7} B_m^{4/7} \tag{44}$$

or, noting that L_m and B_m are of the same order of magnitude and that the product $(L_m B_m)$ is half the area of the column, A,

$$(\sigma^{\#})^{4/7} \cdot \Delta^{\#} \simeq \frac{a_3}{\sqrt{2}}\sqrt{A} \tag{45}$$

which gives an indication of the area required to perform a given separation with a given output when the value of the annular space is at the optimum.

It is also worth noting that parallel plate columns are in general, preferable to concentric cylinder apparatus due to the higher values of B_m they allow. This remark is in contradition with earlier recommendations of using bundles of concentric columns in an heat-exchanger-type arrangement [5, 8].

In many cases it is not possible to achieve the desired degree of separation with one column and it is necessary to use a series of columns through which the mixture is passed. There are several types of arrangements, depending on the output and separation required but those that appear to be the most successful are the «cascade» [40] and the «transverse flow pattern» [42] arrangements.

These types of column batteries require themselves an optimization treatment to obtain the best overall performance but in what concerns the optimization of each individual column the above treatment remains essentially valid.

Before finalizing it must be said that with this new approach, based on the argument that thermal diffusion may be used in large-scale without incurring in any new extra power-cost, the operation costs are solely related with equipment costs — materials + construction + maintenance and depreciation — which are likely to be given by equations of the type

$$\text{Materials cost} = C_1(2L_mB_m) = C_1A \tag{46}$$

$$\text{Labour cost} = C_2 \cdot \frac{L_m}{2\omega} \cdot \frac{B_m}{2\omega} = \frac{C_2}{(2\omega)^2} \cdot A \tag{47}$$

$$\text{Fixed cost} = S \tag{48}$$

and therefore, the operation cost is

$$\Pi = \left[C_1 + \frac{C_2}{(2\omega)^2} \right] \cdot A + S \tag{49}$$

which, indeed is quite different from that predicted by equation (1).

LIST OF SYMBOLS

A — column area
a — constant eq. (2)
a_1 — coefficient defined by eq. (36)
a_2 — coefficient defined by eq. (37)
a_3 — coefficient defined by eq. (40)
B — column width
C_1 — coefficient eq. (46)
C_2 — coefficient eq. (47)
c — molar fraction of the reference component
c_o — feed composition
D — ordinary diffusion coefficient
g — gravity acceleration
H — transport coefficient defined by eq. (23)
K — transport coefficient defined by eq. (24)
k_3 — coefficient eq. (7)
L — column length in the vertical direction
N — speed of rotation
p — power cost per unit of area and unit of time
r — «relative product rate» defined by eq. (27)
r_1 — O. D. inner cylinder
r_2 — I. D. outer cylinder
S — fixed costs per unit of area
T — absolute temperature
T_1, T_2 — wall temperatures
t — time
t_r — relaxation time, eq. (9)
v_z — velocity component in the z-direction
x, z, — rectangular coordinates

GREEK LETTERS

α — thermal diffusion factor
β — $\partial\rho/\partial T$
Δ — degree of separation between the top and bottom of the column
Δ_∞ — steady-state separation
ΔT — temperature difference between the walls ($T = T_2 - T_1$)
η — viscosity
θ — deflection angle from the vertical
λ — dimensionless lenght defined by eq. (10)
ν — «equivalent annulus width» factor, eq. (13)
ξ — dimensionless horizontal distance, eq. (26)
Π — cost-function
π — 3.141592...
ρ — density of the mixture
σ — product flow-rate
Φ — rotary column factor, eqs. (14) to (18)
ω — half distance between the column walls

SUBSCRIPTS

av — average values
b — bottom fraction of the column
t — top fraction of the column
m — in meters
e — enriching section
s — stripping section
RC — Ruppel and Coull
max — maximum
opt — optimum

SUPERSCRIPTS

* — rotary column parameter
# — pre-fixed value

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RESUMO

A separação de misturas liquidas por difusão térmica tem sido considerada com reduzido interesse económico em comparação com outros processos de separação mais conhecidos. As aplicações da técnica têm-se limitado, praticamente, a operações de laboratório como método analítico ou a purificações à escala preparativa. Todavia, nas análises tradicionais sobre as aplicações da técnica não foram tomadas em consideração as características únicas do processo de difusão térmica, nomeadamente a possibilidade de este utilizar virtualmente qualquer gradiente de temperatura a qualquer nível de temperaturas. Esta feição única pode, contudo, ser o factor-chave na estimação da viabilidade económica da difusão térmica à escala industrial. No presente trabalho discutem-se os aspectos principais relacionados com a aplicação da difusão térmica como técnica de separação em operação contínua, descontínua e semicontínua. Discutem-se também os métodos de projectos correntes e propõe-se uma nova metodologia para o projecto de instalações contínuas.

F. L. DA SILVA (1)

T. R. BOTT

Chemical Engineering Department
Birmingham University — U. K.

THE EFFECTS OF SOME PHYSICAL PROPERTIES ON LIQUID THERMAL DIFFUSION SEPARATION (2)

Two cylinder termogravitational columns have been used to study the behaviour of several liquid binary mixtures under the action of a horizontal temperature gradient. It has been found that the relation between the solubility parameters, the molecular weights and the normal boiling points of the components gives no indication as to the component concentrating in each extremity of the column, at steady state. For all but two of the liquid pairs studied the component with the higher density concentrates at the bottom of the column. Some separation data on twenty-six binary systems are presented.

1 — INTRODUCTION

In considering the separation of liquid mixtures by thermal diffusion, TYRREL [1] states that «the compound which accumulates at the cold wall is often that with the highest boiling point and molecular weight». This empirical rule results as a consequence of the direction of separation in liquid systems being in part associated with the heat of vapourization. As a rule, a high heat of vapourization is associated with a high boiling point and a high molecular weight. Tyrrel declares that «the relative magnitudes of the solubility parameters of the two components (of a liquid mixture) usually determines the sign of the separation», and also that «where the solubility parameter is unknown, the compound with the higher molecular weight and high boiling point can usually be relied upon to migrate to the cold wall».

BOTT and WHYSALL [2] by the study of some binary mixtures found some support for Tyrrel's ideas although the system n-dodecane-quinoline showed some differences.

In order to throw further light on the problem of assessing the separation potential of mixtures, a number of binary mixtures have been studied in relation to molecular weight, density and solubility parameter under steady state conditions.

2 — EQUIPMENT

Two stainless steel concentric cylinder thermal diffusion columns have been used for the experiments. Their geometrical characteristics are indicated in Table 1.

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(1) Present adress: Departamento de Engenharia Mecânica — Faculdade de Engenharia — Porto — Portugal.

(2) Presented at CHEMPOR' 75 held in Lisbon, 7-12 September 1975 at the Calouste Gulbenkian Foundation Center.
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Whole set	500
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Environmental engineering	150
Management studies	150

This paper was presented at the Transport processes section.

Table 1

Column No.	Height (in cm)	Out diameter (in cm)	Inner diameter (in cm)	Annulus width (in cm)
1	121.9	2.8454	2.6662	0.0896
2	127.0	2.8875	2.8257	0.0309

Each column was heated electrically by means of a uniform winding of Brightray Nichrome wire on the outside of the outer cylinder. The constancy of the outer wall temperature was assumed and estimated by a thermistor accurate to ± 0.1 °C, using a thiristor as its sensing element.

The inner wall was kept at practically constant temperature by circulation of cold water from a thermostated water tank.

Column No. 1 was also provided with two independent «supplementary» heating circuits, made of Brightray coiled coils, on the outer cylinder extremities, in such a way that the heat losses due to the «end effects» could be compensated by the «suplementary» heaters.

The calculation of these circuits was made according to previous workers' methods [3-6].

The working temperatures were measured by iron-

Table 2

Substance	Boiling point °C	Molecular weight	Solubility parameter at 25 °C in $cm^{\frac{1}{2}}/cm^{1.5}$ δ	Density at 25 °C in gram/cm³ ρ
Benzene	80.1	78.1	9.1	0.874
n-Heptane	98.4	100.2	7.4	0.680
n-Butyric acid	163.3	88.1	10.7	0.953
n-Propanol	97.2	60.1	10.3	0.800
Toluene	110.6	92.1	8.9	0.862
1,1,2,2-Tetrachloroethylene	121.2	165.8	9.3	1.615
Methanol	64.7	32.0	12.9	0.787
Methylcyclohexane	100.9	98.2	8.0	0.765
Diacetone alcohol	168.1	116.2	9.3	0.934
Iso-butylmethylketone	116.5	100.2	8.3	0.796
2-Bromopropane	59.4	123.0	8.3	1.306
n-Hexadecane	286.8	226.4	7.4	0.770
Iso-octane	99.2	114.2	7.0	0.688
Acetophenone	202.0	120.2	10.2	1.024
n-Nonane	150.8	128.3	7.5	0.714
Butanone	79.6	72.1	9.0	0.800
o-Xylene	144.4	106.2	9.0	0.876
Benzyl alcohol	205.4	108.1	13.0	1.041
1-Decanol	232.9	158.3	8.4	0.826
1-Butanol	117.7	74.1	9.8	0.806
1,2-Dibromethane	131.4	187.9	10.4	2.169
1-Hexanol	157.0	102.2	9.1	0.816
Isopropylbenzene	152.4	120.2	8.5	0.858
Ethylbenzene	136.2	106.2	8.8	0.863
n-Octane	125.7	114.2	7.5	0.698
Cyclohexanol	161.1	100.2	10.1	0.968
Bromobenzene	155.9	157.0	10.1	1.488
m-Xylene	139.1	106.2	8.8	0.860
1-Octanol	195.2	130.2	8.7	0.822

constantan thermocouples in conjunction with a Honeywell recorder.
Each column was supplied with two sampling points at the top and bottom of the column.

3 — EXPERIMENTAL TECHNIQUE

The columns were filled by means of a suitable size all glass syringe, through the lower sampling port, until the feed mixture started to issue from the upper port. In order to avoid the contamination of the liquid mixture with some residual liquid, a complete washing of the annulus was always performed before the start of any run. As a rule, two batches of the liquid mixture were sufficient to remove any traces of liquid remaining from the previous run.
In order to heat up the columns, the thiristor and the two «variacs» that control the heating of the extremities of column No. 1 (or the thiristor, only, in the case of column No. 2) were adjusted, after which both the columns were left to run automatically during each experiment. All the runs in either column were carried out at steady-state with temperature differences up to 30 °C and liquid temperatures of approximately 25 °C.
After switching off the heating circuits, 0.1 cc samples were taken from the lower and upper ports. Both samples were immediately analysed by a Bellingham and Stanley high precision refractometer, with an accuracy of 2×10^{-5}, using a sodium line light

Table 3

No.	System		Component concentrating at top
	Component I	Component II	
1	methanol	benzene	I
2	methanol	toluene	I
3	toluene	methylcylcohexane	No separation
4	diacetone alcohol	1,1,2,2-tetrachloroethylene	I
5	iso-butylmethylketone	2-bromopropane	I
6	n-heptane	n-hexadecane	I
7	iso-octane	n-hexadecane	II
8	acetophenone	n-nonane	II
9	butanone	o-xylene	I
10	n-hexanol	benzyl alcohol	I
11	benzyl alcohol	1-decanol	II
12	n-propanol	1,1,2,2-tetrachloroethylene	I
13	1-butanol	1,1,2,2-tetrachloroethylene	I
14	1-butanol	1,2-dibromoethane	I
15	1-hexanol	1,2-dibromoethane	I
16	butanone	benzene	I
17	isopropylbenzene	n-nonane	II
18	ethylbenzene	n-octane	II
19	cyclohexanol	1-hexanol	II
20	benzyl alcohol	1-octanol	II
21	cyclohexanol	bromobenzene	I
22	m-xylene	iso-octane	II
23	n-heptane	1,1,2,2-tetrachloroethylene	I
24	n-butyric acid	1,1,2,2-tetrachloroethylene	I
25	benzene	n-heptane	II
26	n-propanol	toluene	I

source; their refractive indices allow their composition to be estimated (in mole fraction of the reference component, this is the one with the smaller molecular weight). A previously determined calibrated curve was used for this purpose.

4 — LIQUIDS STUDIED

Table 2 gives a list of the liquids used to make up the systems studied in this work together with relevent physical property data.

The solubility parameter, δ, has been defined by Hildebrand [7] and identified with the square root of the internal pressure or «cohesive energy density» of a pure substance:

$$\delta = \left(\frac{-E}{\upsilon} \right)^{\frac{1}{2}} \qquad (1)$$

Use was made of Hildebrand's rule to calculate the latent heat of vapourisation, E, of each liquid.

The value of density and boiling points were obtained from various sources [8-11].

5 — EXPERIMENTAL RESULTS

The results presented in this paper are of a preliminary nature forming only part of a programme of work, and are largely qualitative.

Table 3 shows which component in twenty-six binary systems, concentrates at the top of the particular column.

Table 4 makes a comparison of the data in relation to the physical properties shown in Table 1. Whenever the value of a physical property of the component concentrating in the top of a thermal diffusion column is greater than the value of the corresponding property of the component accumulating in the bottom, such a fact is indicated in Table 4 by the sign $>$. For the opposite situation use is made of sign $<$. When both components have the same value for a particular property, the fact is recorded with an $=$ sign.

From inspection of Table 4 the following observations can be made:

1) It would appear that a comparison of component molecular weight, boiling point or solubility parameter does not give a conclusive indication of how separation is likely to take place.

2) The relationship between the densities seem to give a better indication concerning the migration of the two components of a binary liquid mixture in a thermodiffusion column; the constituent with the smaller density concentrating in the top of the apparatus whereas the other one accumulating at its bottom.

The results by Bott and Whysal [2] and by Jones and Milberger [12] tend to corroborate these operations.

The operating conditions and the quantitative results obtained in the experimental work are contained in Table 5.

Table 4

System No.	B. P.	M. W.	δ	ρ
1	<	<	>	<
2	<	<	>	<
3	NO SEPARATION			
4	>	<	=	<
5	>	<	=	<
6	<	<	=	<
7	>	>	>	>
8	<	>	<	<
9	<	<	<	<
10	<	<	<	<
11	>	>	<	<
12	<	<	>	<
13	<	<	>	<
14	<	<	<	<
15	>	<	<	<
16	<	<	<	<
17	<	>	<	<
18	<	>	<	<
19	<	>	<	<
20	<	>	<	<
21	>	<	>	<
22	<	>	<	<
23	<	<	<	<
24	>	<	>	<
25	>	>	<	<
26	<	<	>	<

Table 5

System No.	Column No.	T_1	T_2	ΔT	C_o	C_e	C_s	Δ_∞
		Degrees centigrade			Mole fraction			
1	1	30.5	20.5	10	0.6897	0.7046	0.6762	0.0284
2	1	30.5	20.5	10	0.7178	0.7327	0.7050	0.0277
3	2	32	21.5	10.5	0.5505	0.5505	0.5505	0.0000
4	1	30.5	20.5	10	0.4625	0.4631	0.4620	0.0011
5	1	30.5	20.5	10	0.4290	0.5360	0.3300	0.2060
6	1	30.5	20.5	10	0.6750	0.7260	0.6280	0.0980
7	2	32	21.5	10.5	0.6410	0.6240	0.6570	0.0330
8	1	30.5	20.5	10	0.6103	0.3994	0.8066	0.4072
9	1	30.5	20.5	10	0.8480	0.8639	0.8337	0.0302
10	1	30.5	20.5	10	0.6206	0.6907	0.5522	0.1385
11	1	30.5	20.5	10	0.6085	0.5566	0.6574	0.1008
12	1	30.5	20.5	10	0.5708	0.6341	0.5132	0.1209
13	1	30.5	20.5	10	0.5301	0.5512	0.5105	0.0407
14	1	30.5	20.5	10	0.4797	0.5398	0.4221	0.1177
15	1	30.5	20.5	10	0.4103	0.4572	0.3673	0.0899
16	1	30.5	20.5	10	0.4943	0.5030	0.4862	0.0168
16	2	32	20.5	11.5	0.2087	0.2816	0.1433	0.1383
17	1	30.5	20.5	10	0.5639	0.3863	0.7376	0.3513
18	1	30.5	20.5	10	0.5775	0.5194	0.6339	0.1145
19	1	30.5	20.5	10	0.5203	0.4704	0.5687	0.0983
20	1	30.5	20.5	10	0.5990	0.5760	0.6203	0.0443
21	1	30.5	20.5	10	0.5089	0.5252	0.4940	0.0312
22	1	30.5	20.5	10	0.4403	0.4289	0.4506	0.0217
23	1	30.5	20.5	10	0.4916	0.6173	0.3756	0.2417
24	1	26.5	16.5	10	0.5275	0.5332	0.5223	0.0109
25	1	36.5	20.5	16	0.6195	0.5567	0.6821	0.1254
26	1	36.5	21	15.5	0.5815	0.5844	0.5789	0.0055
26	2	34.5	21	13.5	0.5816	0.6665	0.5062	0.1603

6 — CONCLUSIONS

The results obtained hitherto are insufficient to allow any conclusions to be drawn as to the extent of the steady-state separation attained, when a binary liquid mixture is subjected to a temperature gradient in a thermal diffusion column. However, it has been shown that the equality of the solubility parameters of both components does not imply absence of separation

It has been shown that the qualitative behaviour (or signe of separation) does not depend upon the relative values of the boiling points, the molecular weights and the solubility parameters. On the other hand the influence of difference in densities of the two components seems to be very important, the component with the larger density concentrating at the bottom of the column; only one exception to this rule was found in the present experiments.

NOTATION

c — mole fraction of the reference component
E — molal latent heat of vapourisation, H
T_1 — hot wall temperature, T
T_2 — cold wall temperature, T

ΔT — temperature difference between the hot wall and the cold wall, in T
Δ_{∞} — steady state separation
δ — solubility parameter, $H^{\frac{1}{2}}$, $L^{-1\ 5}$
ρ — density, ML^{-3}

SUBSCRIPTS

e — enriching (or top) section
s — stripping (or bottom) section
o — initial condition

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RESUMO

Usaram-se duas colunas termogravitacionais cilíndricas para estudar o comportamento de várias misturas líquidas binárias sob a acção de um gradiente de temperatura horizontal. Para estado estacionário, a relação entre os valores da solubilidade, pesos moleculares e pontos de ebulição normais dos componentes não dão indicação de qual o componente que se concentra em cada uma das extremidades da coluna. Com apenas duas excepções, para todos os pares de líquidos estudados, o componente de maior densidade concentra-se na parte inferior da coluna.

J. PEREIRA CARDOSO

CLEMENTE PEDRO NUNES

JOÃO DE DEUS S. PINHEIRO

M. MANUELA P. S. PINHEIRO

Chemical Engineering Department
The University of Birmingham
Edgbaston, Birmingham B15 2TT
U. K.

CONTRIBUIÇÃO PARA A REFORMA DO ENSINO DE ENGENHARIA QUÍMICA EM PORTUGAL (1)

Discutem-se os objectivos a atingir na formação do engenheiro químico por uma análise dos campos de actividade e funções que definem a profissão. Procura-se, seguidamente, avaliar a importância de certos aspectos relevantes na formação, como o treino profissional, educação permanente e especialização, perspectivando-os em contexto universitário e nacional. Propõe-se um currículo detalhado para um curso universitário de 4 anos, prevendo-se a instituição de cursos de pós-graduação eventualmente conducentes a um grau académico. Para cada disciplina proposta, para além da enunciação dos principais tópicos envolvidos, indica-se, também, a ordem de grandeza do número de horas de contacto docente-discente. Pontos salientes do currículo ora sugerido são também a introdução de matérias de engenharia química no 1.º ano do curso, a aplicação mais dirigida das ciências básicas, a larga utilização da matemática e métodos computacionais e a ênfase destacada no trabalho experimental e de projecto. Ao longo do presente trabalho põe-se, também, em evidência a necessidade de se instituirem mecanismos de consulta e grupos de coordenação envolvendo a Universidade, a Indústria, o Governo e, muito em especial, a Associação Profissional de Classe.

1 — INTRODUÇÃO

Resulta o presente trabalho da reflexão conjunta de um grupo de engenheiros químicos, bolseiros em Inglaterra, sobre o ensino (e a aprendizagem) de engenharia química em Portugal, suas metas e constrangimentos, seus dados e variáveis.

O tópico é imenso. Basta retirar sucessivamente uma palavra ao tema do trabalho, obtendo-se «ensino de engenharia química», «ensino de engenharia» e «ensino» para se verificar que a problemática em questão ultrapassa largamente o âmbito mais restrito de uma forma curricular ou de uma reestruturação departamental, embora necessariamente as implique.

A generalização pode ser levada mais longe e chegar à relação biunívoca ensino-sociedade que envolvendo um número de dimensões tendente para infinito fornece, contudo, em última instância, o enquadramento primário para um trabalho deste género: «o ensino (de engenharia química) como qualquer outra actividade deve estar ao serviço da sociedade».

Esta noção de serviço, no caso de uma actividade como a engenharia química, é frequentemente traduzida pela afirmação de que «o engenheiro químico deve ser apto e eficiente. Só assim serve a sociedade». Como tal a afirmação não oferece contestação mas, infelizmente, nem sempre é indicado o que se deve entender por aptidão ou eficiência e, mais raramente ainda, quais os meios a usar no sentido de melhorar a formação dos profissionais em causa.

Com o presente trabalho pretende-se exactamente contribuir para a explicitação dos objectivos a

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Management studies	150

This paper was presented at the Management studies section.

atingir na formação de engenheiros químicos e dos meios para atingir esses objectivos em Portugal, em especial (mas não só) no que respeita ao currículo universitário.

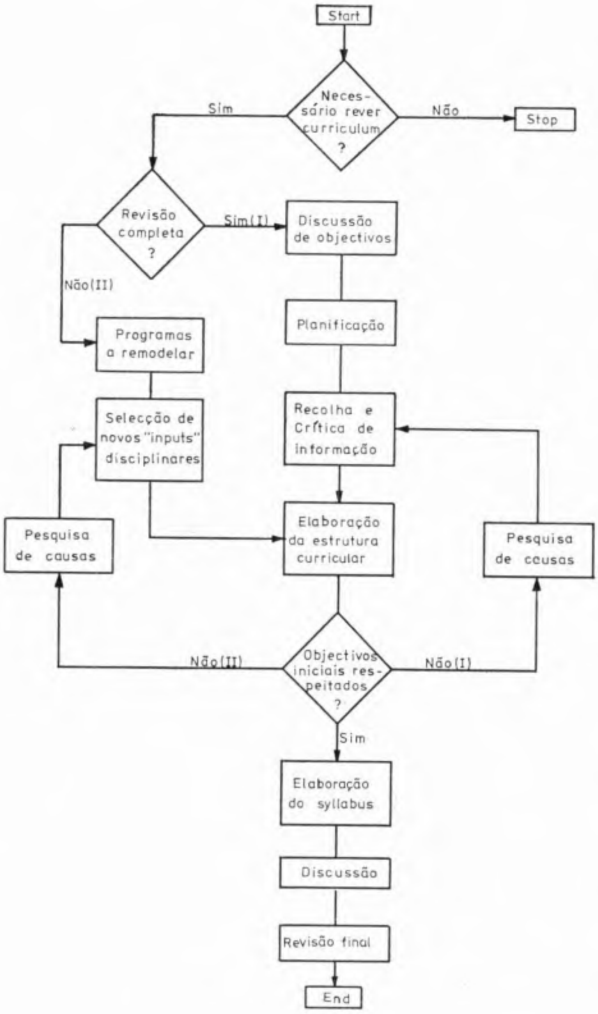

Fig. 1
Diagrama da revisão curricular

É, contudo, importante que desde já fique claro que uma definição correcta de objectivos e meios envolve necessariamente a contribuição de todos os interesses afins — Indústria, Governo e Associação Profissional de Classe — que não somente o corpo universitário.

A metodologia que presidiu à elaboração deste trabalho está sumarizada no diagrama da fig. 1.

2 — O QUE É UM ENGENHEIRO QUÍMICO

«Que é um engenheiro químico?» — é sem dúvida a primeira questão que se põe a quem pretenda analisar a formação de engenheiros químicos. A resposta contudo não é linear como o atestam as actas de inúmeras reuniões internacionais em que se tem debatido o espaço de engenharia química, i.e., as actividades e atitude que têm uma correspondência biunívoca com a profissão [1-7]. E mesmo as definições propostas são tão diversas e genéricas que virtualmente não definem, de facto, a essência da profissão.

Torna-se pois necessário fazer uma excursão, ainda que necessariamente breve, pelo tópico.

2.1 — *EVOLUÇÃO DA ENGENHARIA QUÍMICA*

Embora se argumente que a profissão remonta à idade do bronze, o nascimento, como ramo de engenharia, com o nome que hoje tem, situa-se por alturas do princípio deste século. O curso era dado a nível de pós-graduação e visava cobrir o vácuo entre a química pura e a engenharia mecânica numa base interdisciplinar, sem contudo implicar qualquer disciplina própria [7,8]. As matérias curriculares foram entretanto evoluindo, como evoluindo foi o campo de acção — e o perfil — do engenheiro químico.

Porém, só por alturas da II Guerra Mundial com o aparecimento das grandes indústrias químicas e petroquímicas, e principalmente com o desenvolvimento concomitante de um corpo de conceitos próprios — operações unitárias, «flowsheet» — , o curso de engenharia química ganhou a sua personalidade própria e o reconhecimento como ramo de engenharia independente [7,8].

Nas duas décadas seguintes o desenvolvimento da profissão e do ensino centrou-se em torno do conceito de operação unitária, quer pelo aprofundamento de cada operação, quer pela síntese de processo químico conseguida com base no «flowsheet» via balanços mássicos e energéticos, tudo orientado para a optimização do processo.

Na última década — que hoje vivemos — as «ferramentas» do engenheiro químico sofreram nova mutação devido à expansão de técnicas e equipamento computacional que não só permitem um grau apreciável de estandardização no projecto (englobando mesmo termos de perturbação) como facilitam a utilização crescente de «bancos de informação» ou o emprego de sistemas de controle altamente sofisticados, bem como a solução de problemas primitivamente intratáveis [7-10].

Uma das consequências da aplicação de novas técnicas e ciências à engenharia, bem como o desenvolvimento que as próprias disciplinas de engenharia têm tido, foi a eventual «especialização» em zonas de interesse diversas como «ciências de engenharia química», «desenvolvimento do processo», «sistemas», «controle», etc., cada um já com um apreciável corpo de conceitos e áreas de aplicação.

2.2 — *ÁREAS DE ACTIVIDADE*

Da mesma forma que é corrente a distinção entre ciências fundamentais e ciências da especialidade, é conveniente distinguir no campo tecnológico dois tipos de tecnologias: Tecnologias Primárias, que fornecem uma disciplina mental e um tipo de conhecimentos profissionais que servem um grupo numeroso de áreas de actividade, e Tecnologias Secundárias, próprias de uma determinada indústria ou sector (borracha, vidro, cerâmica, alimentação...) e cujo número — com interesse para o engenheiro químico — tem vindo a aumentar incessantemente.

A análise dos quadros I e II mostra, aliás claramente, que as áreas de actividade do engenheiro químico e as Tecnologias Secundárias que utiliza são de tal forma diversificadas que não é possível caracterizar a profissão de engenheiro químico através delas.

Convirá, por outro lado, referir que a disseminação dos campos de interesse do engenheiro químico encontra a sua justificação na formação básica não especializada em Tecnologias Secundárias e na proveitosa aplicação dos conceitos de optimização e «flowsheet» a processos não convencionais, frequentemente de índole interdisciplinar [5,8,11-13].

Parece pois desaconselhável retirar a ênfase nas Tecnologias Primárias que tem caracterizado o currículo universitário e que se associem mais directamente ao tipo de actividade funcional do engennheiro químico.

Quadro 1

Áreas de emprego após a formatura, no Reino Unido [12, 13]

Sector	Distribuição (%)				
	1953	1963	1969	1971	1972
— Indústria Química Pesada (Orgânica e Inorgânica)	18,0	23,7	21,1	6,4	7,0
— Indústria Química Fina (Perfumarias, Farmácia...)	9,0	9,7	7,3	4,6	2,1
— Resinas, Sintéticos, Plásticos	5,7	4,9	4,5	2,0	1,4
— Alimentação, Tabaco, Bebidas	3,7	2,5	1,9	4,6	3,9
— Têxteis	2,2	3,5	3,1	3,1	3,9
— Cimento, Vidro, Refractários, Mineração (não carbonífera)	3,5	4,4	0,4	2,1	2,1
— Papel, Pasta, Aglomerados	1,5	0,6	1,7	0,4	0,1
— Petróleo, Carvão	13,6	16,6	7,1	7,6	3,4
— Gás, Energia, Águas	10,9	6,7	5,4	6,8	1,0
— Instrumentação, Controle, Construção de Equipamento, Consultor Técnico	20,8	15,5	15,3	10,3	4,3
— Ensino e Investigação	10*	10*	25,9	30,2	19,9
— Outros	1,1*	1,9*	6,3	21,9	50,9

* Valor estimado.

Quadro II

Áreas não tradicionais de crescente interesse para o engenheiro químico [6, 12, 39, 40]

ENERGIA	Produção Transmissão Consumo
ALIMENTAÇÃO	Produção de alimentos sintéticos Conservação de alimentos Processamento (fermentação, refinação, secagem, embalagem, etc.)
AMBIENTE/POLUIÇÃO	Controle de poluição industrial Tratamento e reciclagem de efluentes
ÁGUAS	Reciclagem e reaproveitamento Tratamentos Dessalinização Oceanografia
AGRICULTURA	«Spraying» «Composting» Armazenamento e secagem de cereais

2.3 — *FUNÇÕES DO ENGENHEIRO QUÍMICO*

A mais simples e mais vulgarizada classificação de funções do engenheiro químico baseia-se nas chamadas quatro fases do processo químico:

1) Desenvolvimento do Processo e Investigação.
2) Projecto e Cálculo do Equipamento.
3) Construção e Arranque.
4) Operação, Manutenção e Optimização.

Convirá aqui enunciar, ainda que genericamente, o que cada uma destas divisões comporta para que se possa compreender melhor as bases de formação propostas.

Assim o Desenvolvimento do Processo e Investigação compreende o estudo de processos novos ou o melhoramento de processos já existentes. Procura-se obter informação acerca das diferentes reacções ou operações através das quais um determinado produto pode ser obtido, do rendimento das várias etapas do processo, de prováveis processos de corrosão e ainda uma avaliação de custos e fornecimentos de matérias-primas e outros «inputs» do processo.

A fase seguinte — Projecto e Cálculo — respeita ao estabelecimento do «flowsheet» com indicação da capacidade e outras características fundamentais das diversas partes do equipamento. Esta fase assume foros de zona crítica, na medida em que dela depende em grande parte o êxito (eficiência, facilidade de controle, etc.) da instalação e é por vezes confundida com a designação mais lata do projecto. A parte final desta fase compreende o cálculo detalhado das diversas peças do equipamento ou a selecção no caso de peças estandardizadas (ex. bombas centrífugas...).

Na chamada «Operação ou Fabrico» o engenheiro químico ajudará a manter em operação uma dada linha de produção.

Em muitos casos estas funções envolverão muito de gestão — de pessoal, de equipamento, de «stocks»... — , noutros casos a função será mais científica, i.e., mais virada ao controle de qualidade, à eficiência global e de items parcelares, nomeadamente à redução de custos energéticos ou de poluição ou ainda de manutenção, e envolverá um certo grau de investigação dirigida.

Naturalmente, o engenheiro de fabrico será em alto grau um «solucionador de problemas» não só remediando situações imprevistas mas também eliminando problemas potenciais («trouble-shooter»).

É evidente que nesta função deve o engenheiro químico muito à experiência e capacidade pessoal, factores cuja importância não é de mais realçar.

Quadro III

Distribuição funcional dos profissionais de engenharia química no Reino Unido [13, 14]

Actividade funcional	Distribuição (%)		
	1953	1968	1972
Administração e Gestão	25,6	20,2	25,1
Investigação e Desenvolvimento de Processo	27,1	21,8	24,1
Projecto, Construção e Instalação	20,1	20,4	21,6
Operação, Produção e Manutenção	12,5	22,8	12,9
Vendas e Serviços Técnicos	5,4	2,0	5,4
Ensino (e Investigação), Consultor Técnico e outros	9,3	12,8	10,9

Na optimização, como o próprio nome indica, busca-se o ajustamento da operação às condições supostas óptimas e depende essencialmente do processo em causa. Frequentemente nesta função englobam-se os problemas relacionados com o controle das variáveis do processo.

De um ponto de vista pragmático esta divisão de funções está correcta e pode ser bastante útil na definição de uma estratégia de treino (estágio) profissional ou na elaboração de um currículo tecnológico. Peca, porém, a mesma por se afastar apreciavelmente da realidade e de nada dizer acerca da distribuição de profissionais por aquelas funções ou da ênfase em campos não estritamente tecnológicos que elas envolvem [8,12-IV)]. Visões mais realistas são dadas por HOUGEN [7] e NONHEBEL [15], nelas sendo incluído certo tipo de funções não exclusivamente técnicas mas que a experiência demonstra serem desempenhadas — em proporções importantes — por engenheiros químicos (fig. 2).

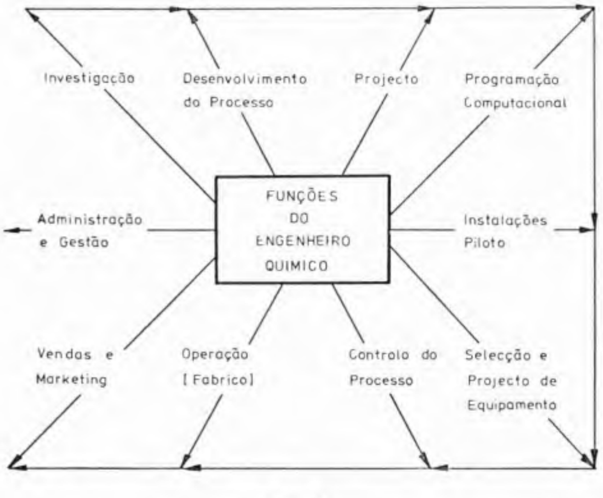

Fig. 2
Actividades funcionais do engenheiro químico segundo Hougen e Nonhebel

A este respeito têm sido publicados alguns dados — quadro III — que mostram a justeza das divisões propostas por Hougen e Nonhebel, sendo ainda de evidenciar a elevada percentagem de engenheiros químicos ligados a actividades de ênfase não tecnológica.

Uma lição a tirar do exposto é a de que a formação do engenheiro químico deve não só ser diversificada pelas várias funções como aplicada a problemas interdisciplinares fazendo intervir factores de gestão, economia e ambiente que em muitos casos são decisivos em termos de viabilidade de um projecto.

Vê-se também que uma das formas de dar ao engenheiro químico uma formação relativamente completa (em termos de funções) será através da elaboração de projectos tanto quanto possível exaustivos durante o curso universitário (e, naturalmente, fazendo apelo a conceitos de análise económica — custos e viabilidade —, de análise social — poluição, emprego, etc.) [16].

De interesse, em especial serão os chamados «Projectos abertos» («open ended project») que a nível individual ou em seminário permitirão a inserção da engenharia química na realidade exterior e poderão assentar numa base interdisciplinar [18].

2.4 — *ALGUMAS DEFINIÇÕES DE ENGENHARIA E ENGENHARIA QUÍMICA*

É possível agora apresentar e compreender algumas das definições correntes de engenharia e engenharia química que se julga representativas. Assim, quanto à definição de «engenheiro», a EUSEC (Engineering Societies of Western Europe and the USA) estabelece que, por definição, «um engenheiro é competente devido à sua formação e ao treino adquirido, em aplicar o método científico à solução dos problemas de engenharia. Está preparado para assumir responsabilidade pessoal pelo desenvolvimento e aplicação das ciências de engenharia e conhece os campos de investigação, projecto, constituição, fabrico, gestão, organização e educação em engenharia química. O seu trabalho será predominantemente intelectual e variado e não de rotina quer mental quer física. Requererá o exercício de pensar e agir originalmente e a capacidade de supervisionar o trabalho técnico e administrativo de outros.

A sua formação deverá ter sido tal que lhe permita o acompanhar de perto o evoluir das ciências da engenharia através de revistas da especialidade estando portanto apto a aplicar os desenvolvimentos das mesmas.

A sua formação e treino profissional deverão ter-lhe permitido «entender» os outros ramos da engenharia e os vários campos secundários do seu próprio ramo.

Deve, em suma, poder dar opiniões técnicas com autoridade e responsabilidade».

A definição da EUSEC refere-se pois ao profissional de engenharia no que ele deve implicar de metodologia intelectual. A metodologia científica liga-se, naturalmente, ao particular ramo de engenharia em causa que, por seu turno, também não é fácil de definir em poucas palavras. No caso da engenharia química a questão agudiza-se pela extensa diversificação de funções e áreas de actividade a ela associadas [4,19-21], e de tal sorte que as «propostas de síntese» a seguir referidas só fazem, de facto, sentido após a análise» que para trás ficou.

A «Enciclopédia Britânica» indica que «engenharia química é o ramo de engenharia relacionado com o projecto, construção e operação de unidades industriais nas quais os materiais sofrem modificações de estado ou composição». Um ponto de vista semelhante é dado por DANCKERTZ [19] ao referir que «a engenharia química respeita aos processos nos quais ocorrem alterações de composição ou de propriedades da matéria».

Uma visão mais exaustiva é dada pela A.P.C. britânica (1.Ch.E., U.K.): «A engenharia química é o ramo da engenharia que trata dos processos nos quais a matéria sofre transformações de composição, conteúdo energético ou estado físico e dos meios práticos do processamento com o fim de obter produtos que possam ser úteis (em si mesmo ou como parte do fabrico doutro produto).

A engenharia química tem as suas bases disciplinares na matemática, física e química no sentido em que as suas operações usam conhecimentos fornecidos por estas ciências bem como por outros ramos de engenharia, ciênciasa plicadas, biológicas e sociais.

A prática de engenharia química relaciona-se com a concepção, desenvolvimento e optimização de processos e aplicação dos produtos com as áreas de projecto, construção, operação, controle e gestão de unidades industriais nas quais os processos ocorrem e com a investigação e formação científica que estes campos de actividade encerram.»

Acrescenta-se ainda, uma citação de SOUDERS [20] que em grande parte suporta os argumentos que se têm vindo a desenvolver: «Muito se tem vindo a dizer acerca da diversificação de ocupações dos engenheiros químicos e da extensa área de actividade industrial de engenharia química. À primeira vista a multiplicidade de funções parece excluir a possibilidade de as classificar ou de se elaborar um grupo de actividades profissionais desejáveis ou mesmo de se definir o conteúdo da sua educação. Mas... o engenheiro químico é aquele que tem consciência de que as temperaturas locais diferem das temperaturas globais; que as experiências laboratoriais não são nem adiabáticas nem isotérmicas; que um reservatório é tanto mais barato quanto mais estreito; que o coração de um sistema de controle é o sinal primário; que a mistura não é instantânea: ele sabe que as paredes do reservatório fazem parte do sistema reaccional; que não é uma diferencial exacta; que, na prática, quantidades mínimas de impurezas podem acumular-se ao longo do processo e alterar a reactividade do catalisador ou doutra superfície. Ele conhece os compromissos a estabelecer entre os requisitos da química-física e a construção mecânica; que projectos tecnicamente viáveis são frequentemente antieconómicos; que as unidades de fabrico reais estão constantemente sujeitas a fugas, falhas e má operação. O engenheiro químico sabe isto e mais. Aprendeu-o parcialmente nos cursos fundamentais e muito especialmente nos problemas de «design» na escola e na prática. Se não os aprendeu, então terá graves dificuldades no exercício da profissão ainda que disponha de profundos conhecimentos de ciência teórica.»

3 — A FORMAÇÃO DO ENGENHEIRO QUÍMICO

3.1 — *DELIMITAÇÃO DO PROBLEMA*

É conveniente distinguir «ab initio» duas vias complementares na formação do engenheiro químico: «via empírica», que também se poderia designar por «saber de experiência feito» e que só o exercício pleno da profissão vai assegurando, e a chamada «via científica», em que determinado tipo de conhecimentos se adquire através do estudo sistematizado. No presente trabalho a ênfase é naturalmente colocada na via científica o que implica a apreciação das estruturas existentes (ou inexistentes) que concorrem para a formação do engenheiro químico, bem como dos condicionalismos com que à partida teremos de entrar em conta ao propormos eventuais linhas de acção. Numa fase posterior poder-se-á então focalizar a discussão nas estruturas disciplinares e metodológicas do principal suporte da formação científica dos engenheiros químicos: o curso universitário.

3.2 — *AS FONTES DO SABER*

Ao pretender-se analisar a formação científica em engenharia química verifica-se que, à parte raras excepções, a grande maioria dos trabalhos nesse campo é oriunda de países altamente industrializados, traduzindo naturalmente as preocupações e objectivos dos mesmos. Em consequência, a menos que uma função crítica seja sistematicamente exercida sobre estas «fontes do saber» corre-se o risco grave, de definir padrões de formação que pouco terão a ver com a realidade nacional. O problema não é novo e já AWOKOYA, responsável pela UNESCO, o apontava ao dissertar sobre a formação profissional em países não desenvolvidos [22].
E, de facto, será suficiente enunciar algumas das premissas adjacentes aos currículos universitários em países como os EUA, URSS ou Grã-Bretanha para que se compreenda um pouco melhor as condições «à partida» naqueles países [8,23]:

1) O estudante dispõe e utiliza em larga medida livros e revistas da especialidade na própria língua, laboratórios experimentais e instalações-piloto, tendo ao dispor adequadas facilidades computacionais.

2) A especialização a nível universitário numa função (ramo) de Engenharia Química ou numa Tecnologia Secundária é desejável e deve ser função dos recursos humanos e materiais da escola. O elevado número de instituições universitárias assegura virtualmente a necessária diversificação de especializações.

3) Após e durante o curso universitário segue-se um período de treino profissional sob orientação de profissionais competentes e de acordo com as recomendações da Associação Profissional de Classe (A.P.C.).

4) A Universidade não confere títulos profissionais. Estes são conferidos pela A.P.C. após aprovação do diplomado no treino pós-universitário de acordo com as normas estabelecidas pela A.P.C.

5) A existência de múltiplos cursos de aperfeiçoamento e reciclagem de duração variável permite ao profissional evitar a obsolescência através de uma educação ou formação permanente.

Vejamos mais em pormenor o que alguns destes pontos encerram.

3.3 — *TREINO PROFISSIONAL E PROFISSIONALIZAÇÃO*

Multiplas têm sido as razões apresentadas para a implantação de esquemas de treino profissional que façam a ponte entre a formação científica universitária e a formação empirica da prática profissional [8,15,16,24-27].
O tipo de argumento utilizado é essencialmente redutível a:

1) A engenharia química é uma actividade de larga escala em que a problemática científica se enquadra de forma diferente dos modelos de pequena escala (ver definição de SOUDERS [20] na secção 2.4). Logo, haverá que permitir ao recém-diplomado a adaptação da sua bagagem científica às novas condições ambientes.

2) «Há 60 anos a engenharia química era 99 % de arte e 1 % ciência e, apesar da evolução, ainda será em partes sensivelmente iguais ciência e arte» [8,25]. É pois necessário que a arte do recém-diplomado cresça organizadamente durante um certo período sem carregar ainda o peso da responsabilidade subentendida à sua profissão (ver definição da EUSEC na secção 2.4).

Em Portugal, outros argumentos de índole mais ou menos local, como a inexistência de instalações-piloto na Universidade, ainda seriam adutíveis a justificar a reimplantação em moldes contudo totalmente diferentes dos chamados «estágios».
Porém, no nosso caso, o problema vai um pouco mais fundo e insere-se já no anacronismo vigente de o título profissional ser conferido pela instituição

universitária, o que em última análise equivale a considerar que a formação científica básica, para além de condição necessária, é também suficiente para o cabal exercício da profissão.

Mas se o recém-diplomado não é um profissional no verdadeiro sentido da palavra, quando o passa a ser? Aqui reside sem dúvida o ponto controverso da questão, e até porque dos sistemas em vigor noutros países nenhum parece ser isento de desvantagens. Contudo, só a A.P.C. terá capacidade para se pronunciar sobre qual o sistema desejável para Portugal.

Uma vez porém que o processo de profissionalização esteja definido será mais fácil planear esquemas de treino profissional que respondam aos requisitos estabelecidos pela A.P.C. É crível todavia que qualquer esquema de treino profissional deva assumir as seguintes características [16,17,28]:

1) Esquemas de treino propostos pela Indústria e aprovados não pela Universidade (ainda que se possa pronunciar) mas pelo órgão próprio da A.P.C.

2) Envolvimento das quatro fases principais da indústria química descritas em 2.3.

3) Elaboração de um relatório final de acordo com normas a estabelecer pela A.P.C. e obrigatoriamente discutido pela A.P.C. que requererá os acessores adequados.

No que se disse, pressupõe-se o caso mais geral de o treino ou estágio ocorrer numa fase pós-universitária. Mas, é importante notá-lo, tal não tem que ser necessariamente assim. De facto, outras alternativas são possíveis, entre as quais os chamados cursos «sandwich» ou «co-op» em que o estudante alterna períodos na Universidade e na Indústria, da ordem dos 6 meses a um ano conforme os casos. Este tipo de curso, de origem recente, tem-se expandido rapidamente, em especial nos EUA e Reino Unido em parte pela grande aceitação que os diplomados com estes cursos têm encontrado. Em Portugal, a implantação destes cursos seria desejável, não só pelas razões que estão por detrás desta formação científica/prática simultânea mas porque isso permitiria também, por um lado, descongestionar as universidades e, por outro lado, supriria graves deficiências de equipamento experimental dos laboratórios das nossas universidades.

A grande dificuldade para o oferecimento destes cursos em Portugal reside na ausência de canais de consulta e de grupos de trabalho integrando a A.P.C.-Universidade-Indústria e na dispersão do pessoal docente qualificado para soerguer as linhas de orientação pedagógica de cursos deste tipo.

Entende-se, porém, que será de encorajar a implantação, pelo menos a título experimental, deste tipo de cursos em Portugal que, julga-se, poderiam ser numa primeira fase oferecidos a estudantes-trabalhadores, utilizando os períodos de férias de Verão para o tempo lectivo universitário que eventualmente assumiria um carácter intensivo, de forma a que o número de anos do curso se aproximasse tanto quanto possível da duração do curso normal.

3.4 — *OBSOLESCÊNCIA E EDUCAÇÃO PERMANENTE*

Bastaria atentar na evolução curricular do curso de engenharia química nas últimas décadas [8,10] para que o problema da obsolescência precoce do engenheiro químico se impusesse como uma questão prioritária a requerer um esforço apreciável de educação permanente. Mas, a acrescentar à evolução natural das ciências e técnicas da engenharia química, tem-se nos últimos anos vindo a assistir à profunda reconversão das tecnologias tradicionais devido principalmente ao crescente uso de computadores e, mais recentemente, ao espectacular aumento do preço da energia. Compreende-se assim certo tipo de recomendações que as A.P.C., as universidades e mesmo o governo de alguns países têm feito no sentido de se instituir a educação permanente de uma forma organizada, através de cursos de pequena e média duração de reciclagem e aperfeiçoamento [29-31].

É possível antever, desde já,que aqueles cursos terão de ser organizados numa base mista A.P.C./Universidade e cobrirão fundamentalmente campos disciplinares ou técnicos e mais raramente campos funcionais. Estes por definição são estáveis, o que muda em geral são as «ferramentas». Desse modo parece razoável oferecer, a nível de currículo universitário, um certo grau de especialização no que respeita às funções do engenheiro químico e cobrir os tópicos disciplinares ou técnicos relativos a faixas de conhecimento mais específicas através de cursos intensivos de pequena duração. Ter-se-ia assim cursos tais como [29,32]:

- Reciclagem (de conhecimentos anteriormente adquiridos)
- Aperfeiçoamento (aquisição de novas técnicas)
- Especialização (numa faixa específica) em que se tratariam, por exemplo:
  - Uso de métodos estatísticos
  - Uso de métodos computacionais
  - Introdução ao uso de computadores
  - Gestão de «stocks»
  - Destilação multicomponente
  - Métodos não convencionais de separação
  - Catalisadores industriais
  - Tecnologias secundárias (óleos, combustíveis, papel, etc.)

Atendendo à experiência estrangeira neste campo [12,29] é de recomendar curso de duração média de uma semana com tópicos acordados pela A.P.C.-Universidade. Quanto à inserção no currículo universitário de especializações em funções (ou ramos) de engenharia deve deixar-se essa frequência ou especialização à consideração dos interesses oferecendo-as a nível de pós-graduação [8,12,32-35].
Paralelamente a estes cursos é importante que se revitalizem as publicações em língua portuguesa de autores portugueses em que tópicos de interesse geral seriam tratados, mais concretamente, em que cada engenheiro químico pudesse contribuir com um certo «valor acrescentado» para o conhecimento ou compreensão de uma matéria. Sugere-se mesmo um nome: «Cadernos de engenharia química», e em princípio nada obsta a que não fosse um suplemento doutras publicações já existentes.

3.5 — *FACILIDADES DE ESTUDO*

O ponto presente requer, para completo tratamento, uma inventariação de possibilidades que não é viável fazer aqui. Assim, apenas se apontarão as necessidades mais prementes a remediar a curto prazo:

1) Publicações
É importante que se disponha de textos em português, dignos e actuais (ainda que de edição barata e capa não luxuosa). É porém, ainda mais importante que os alunos e professores tenham acesso à bibliografia estrangeira através de um sistema de consulta facilitada.

2) Laboratórios experimentais
Um verdadeiro laboratório não se compra, constrói-se. Haverá pois que dispor de facilidades oficinais adequadas. Além do mais, só com laboratórios adequados será possível a Universidade colaborar activamente e preparar os seus próprios doutorados.

3) Computadores
Se nalgum sítio a sua utilização se justifica é sem dúvida na Universidade, embora desde já se considere que a sua utilização por organismos exteriores é desejável dentro, aliás, do espírito de serviço que deve presidir à instituição universitária.

4) Uso de laboratórios não universitários
Este é um ponto a encarar em estudos dos últimos anos relacionados com o projecto industrial ou o projecto aberto, mas que terá de resultar de um esforço de organização Universidade--Indústria.

3.6 — *ESPECIALIZAÇÃO EM ENGENHARIA QUÍMICA*

É frequente encontrarem-se na literatura referências à necessidade de se criarem especializações a nível universitário e, em muitos currículos de engenharia química em países desenvolvidos, é vulgar o oferecimento de múltiplas vias de especialização[23, 24,26].
É importante todavia, analisar mais em detalhe que tipo ou tipos de especialização é possível oferecer ao nível universitário relacionados com o curso básico de engenharia química:

1) Especialização disciplinar em que se pressupõe a ampliação do «syllabus» de matérias-base do curso.

2) Especialização interdisciplinar em que a for-

mação básica em engenharia química é ligada a outras ciências como no caso das engenharias bioquímica ou têxtil.

3) Especialização numa tecnologia secundária (exemplo, vidro, cerâmica, cerveja, papel, combustíveis, etc.).

4) Especialização funcional ou num ramo em que se desenvolvem as partes essenciais relacionadas com uma das funções referidas atrás (Produção, Desenvolvimento do Processo, etc.).

A especialização disciplinar referida em 1) interessará, em princípio, a indivíduos que queiram seguir uma carreira de investigação académica ou industrial. Em Portugal, em que o corpo docente universitário tende a ter uma experiência razoável neste campo, não parece que haja dificuldades de maior em oferecer este tipo de especialização.

O interesse da especialização interdisciplinar (n.º 2) em certos campos como a engenharia bioquímica ou engenharia do ambiente, por exemplo, não necessita ser realçado e é convicção dos autores que se assistirá, nos próximos anos, a uma ainda maior ênfase nas especializações interdisciplinares em parte justificadas pelo ónus que apresenta a construção de um curso independente formado à base de «approach» interdisciplinar destas especializações. O oferecimento destas especializações dependerá de vários factores dos quais os mais salientes serão o grau de atracção dos potenciais interessados, a existência de gente da Universidade e da Indústria capaz de tomar as rédeas de alguns assuntos e das características do mercado para estes especialistas bem como dos interesses nacionais. Julga-se que, aqui como em tantos outros campos, o grupo de trabalho A.P.C.-Universidade terá uma palavra importante a dizer.

As especializações em Tecnologias Secundárias — ponto 3 atrás citado — envolvem argumentos muito semelhantes aos anteriores com a diferença que em geral estão associados a uma ou duas indústrias, o que virtualmente lhes retira o interesse lato ou geral que deve ser desejável.

Por outro lado, o mercado tenderá a saturar-se durante um período de tempo relativamente longo, o que obrigaria a alternâncias da ordem dos seis ou mais anos. Deste modo, parece que aspectos ligados a Tecnologias Secundárias devem ser oferecidos a nível de pequenos cursos cobrindo, se possível, áreas de interesse apreciável como, por exemplo, combustíveis, materiais de construção madeira e papel, etc. Resta analisar a especialização funcional que tenderá a associar-se a funções do engenheiro químico atrás referidas. Ao contrário das anteriores, a especialização funcional interessará a um número vasto de diplomados, já que encontra aplicação potencial praticamente em todas as áreas de actividade do engenheiro químico.

Naturalmente a ênfase não poderá ser a mesma para todas as funções do engenheiro químico já que em Portugal a profissão tem estado mais dirigida para a produção e management, e muito pouco ao projecto de equipamento, investigação industrial ou ao Desenvolvimento do Processo. Porém, a menos que queiramos continuar a importar um «know-how» (cada vez mais oneroso) e a actuar como um mero agente de transformação do produto, é importante que as nossas capacidades sejam dirigidas para os planos do «know-how» onde temos razoáveis possibilidades de competir internacionalmente. Referimo-nos aqui ao Desenvolvimento do Processo, zona que nos parece prometedora dentro de um esforço de reconversão das indústrias de engenharia química.

3.7 — *AS ESTRUTURAS PEDAGÓGICAS*

Sendo o curso superior a chave que abre a porta da formação científica do engenheiro químico é importante que as suas estruturas sejam analisadas com algum detalhe. Assim, começa-se por distinguir entre dois níveis estruturais complementares do curso:

1) Estrutura disciplinar a que corresponde um certo tipo de disciplinas com um determinado «syllabus» e creditadas de um certo número de horas.

2) Estrutura pedagógica ou metodológica, ou seja, a atitude intelectual que preside ao prosseguimento do currículo.

Mas, enquanto a nível disciplinar é concretizável através de programas bem definidos (que se apresentam na secção seguinte), o nível metodológico dependerá em vasta eescala da motivação e for-

mação dos corpos docente e discente. No presente trabalho procurar-se-ão definir linhas gerais de orientação pedagógica, que parecem relevantes, juntamente com uma proposta curricular detalhada. O presente conjunto de proposições procura vincar um certo número de pontos de vista pedagógicos julgados pertinentes no contexto de formação desejável para o engenheiro químico. Porém, «a virtude depende do desejo (subjectivo) de a alcançar», e como tal haverá que obter o concurso de todos os interessados, em especial alunos e professores, no sentido de se definirem orientações certas.
A «nossa plataforma» é, em suma, traduzível por:

1) O conhecimento de ciências básicas é pré-requisito para a aprendizagem das ciências de Engenharia Química mas deverão ser ensinadas e aprendidas como um meio e não como um fim.

2) O ensino das ciências de Engenharia Química deve virar-se sempre para o aspecto da utilização prática e deve em muitos casos aceitar a interdisciplinaridade envolvida. Os problemas não devem utilizar apenas dados técnicos mas, desde o início, fazer intervir as «leis da sociedade». Nomeadamente, haverá que incutir no estudante que custos, poluição, etc., são indistinguíveis da produção técnica do produto X.

3) Não é possível ensinar a prática real na Universidade a menos que ela faça parte do currículo (cursos «sandwich»). É, contudo, possível orientar a formação para a prática real através do estudo de problemas reais e da experimentação adequada. Por outro lado, embora seja mais eficiente aprender a prática na indústria, esta raramente poderá seleccionar problemas para treino do nóvel engenheiro ou corrigir erros de formação intrínsecos.

4) O estudante tende a aprender o que realmente executa. Se ouve aulas, faz problemas-tipo e exames; então é isso que ele saberá fazer. Se a aprendizagem depende exclusivamente do professor, então o aluno torna-se dependente do professor. Mas, se, pelo contrário, aprender engenharia química com uma metodologia correcta, poderá utilizar os conhecimentos científicos na solução de questões novas não «calistas». Se os problemas postos ao estudante forem um desafio à sua capacidade de utilizar conhecimentos e não um regurgitar de fórmulas ou métodos mecânicos de resolução, se o estudante for «ab initio» responsável, então ele aprenderá a metodologia da profissão. A verdadeira avaliação de conhecimentos faz-se na prática profissional. Porém, presta-se um mau serviço à sociedade se engenheiros incompetentes forem autorizados a exercer (para além dos graves riscos que comporta).

5) O estudo privado deve ser incentivado e orientado de acordo com as características de cada um. As aulas serão apenas um complemento onde o significado físico dos fenómenos e exemplos de aplicação prática sejam debatidos. O ideal será o estudante chegar à aula conhecendo antecipadamente a matéria.
Em geral, será preferível fornecer menos informação se por via disso se obtém uma melhor formação.

6) Os investimentos a despender com o ensino de engenharia química deverão garantir a formação de diplomados em qualidade e quantidade adequadas às necessidades do País.

7) À luz do parágrafo anterior, cada departamento de engenharia química deverá definir o número de alunos a admitir, de forma a garantir-se que, com os meios materiais e humanos de que o departamento dispõe, os alunos tenham possibilidade de alcançar uma preparação que lhes permita exercer a profissão com proveito para os próprios e para a sociedade.

4 — PROPOSTA DE CURRÍCULO

Como corolário das considerações até agora feitas o curriculo do curso que agora se apresenta toma em consideração mais os seguintes aspectos:

1) O curso de engenharia química, tal como tem sido ministrado nas universidades portuguesas, só muito tarde introduz o estudante em matérias propriamente ditas de engenharia química, o que implica um afastamento dos problemas reais que

constituem o objectivo primeiro da sua formação profissional até uma altura muito avançada do curso, provocando dois grandes inconvenientes:

a) as matérias de formação básica são dadas, como é o caso da matemática, sem aplicações a problemas que o estudante sente como sendo relevantes para o curso que escolheu e poderá por isso contribuir para que surja a ideia de que a matéria em estudo não lhe é fundamental;

b) cumulativamente, quando finalmente se lhe deparam disciplinas de engenharia química, o estudante corre o risco de já não saber utilizar devidamente as ferramentas que anteriormente lhe foram dadas.

Na presente proposta procura-se introduzir os objectivos de engenharia química e as disciplinas que se lhe referem o mais cedo possível.

2) Nos últimos dez anos, os métodos matemáticos capazes de ser facilmente tratados por computadores têm sido progressivamente utilizados para resolver problemas de engenharia química e melhorar extraordinariamente o rigor dos resultados. Para além de a matemática e de os métodos computacionais e numéricos serem extensivamente tratados em disciplina própria, com numerosas aplicações, deverão também ser incluídos em disciplinas de engenharia química tal como Reactores e Operações Unitárias.

3) A formação de um engenheiro químico, tal como já foi salientado, será de incluir prolongado contacto com aparelhagem experimental em que o estudante possa aplicar os conhecimentos de engenharia que vai adquirindo e, ao mesmo tempo, executar projectos experimentais que estimulem e ponham à prova a sua capacidade de enfrentar problemas reais.

Relativamente ao programa elaborado, são de salientar os seguintes pontos:

4) Está estruturado de modo a dar uma formação básica em engenharia química em quatro anos, o que poderá contribuir para um maior aproveitamento do investimento feito na formação de cada engenheiro químico. Deverá, uma vez mais, salientar-se que se pressupõe um elevado grau de profissionalismo de discentes e docentes.

5) Envolve um leque bastante vasto de disciplinas espalhadas pelos quatro anos lectivos considerados. Para que ele se mantenha homogéneo e coerente para quem o frequente é necessário que haja uma estreita colaboração entre todos os membros do corpo docente, preferencialmente através de um conselho pedagógico que deverá envolver também alunos. Na mesma ordem de ideias a existência de disciplinas em atraso dificilmente se poderá conceber.

6) A redução da duração do curso-base de engenharia de cinco para quatro anos torna altamente desejável, e como já foi largamente referida, a criação de cursos de pós-graduação. Estes cursos poderão pois revestir a seguinte forma (ver 3.6):

a) aprofundamento de matérias relacionadas com engenharia química numa certa área de especialização;

b) estudo de Tecnologias Secundárias com carácter interdisciplinar (poderá referir-se a uma indústria com importância local ou regional em que o departamento funcionará como suporte científico e tecnológico);

c) especializações curtas;

d) cursos de reciclagem de curta duração, normalmente sobre matéria de desenvolvimento recente.

7) A existência de investigação em engenharia química é fundamental não só para garantir a relevância dos trabalhos práticos e projectos, mas também para que as matérias ministradas acompanhem a evolução dos conhecimentos de engenharia química [36-38].

Apresenta-se a seguir o esquema curricular para o curso de engenharia química. Julga-se de utilidade indicar o âmbito de cada disciplina proposta através da enunciação dos principais tópicos a serem abordados e do número de horas semanais de contacto supostas convenientes. Entendam-se, contudo, estas recomendações como um instrumento de trabalho ou uma directriz a partir da qual a estrutura de cada disciplina e horas de contacto sejam ajustadas.

PRIMEIRO ANO

PRIMEIRO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
ANÁLISE MATEMÁTICA	— Convergências e limites — Funções de uma variável contínuas e descontínuas; teorema de Taylor. Aplicações. — Derivação. Máximo e Mínimo. Funções exponenciais logarítmicas e hiperbólicas; números complexos; representação gráfica de funções	7
ÁLGEBRA LINEAR	— Álgebra vectorial: produto escolar; produto vectorial — Álgebra matricial; inversão de matrizes. Determinantes. Sistema de valores próprios — Solução de sistemas de equações lineares e quadráticas	4
INTRODUÇÃO À PROGRAMAÇÃO COMPUTACIONAL	— Tipos de informação requerida pelos computadores; linguagem dos computadores e dos compiladores — Fortran IV: descrição da sua estrutura e instruções básicas — Problemas em que o estudante tem de obter a solução correcta por intermédio do computador. Exemplos: equações não solúveis por métodos analíticos; cálculo de propriedades físicas a partir de equações de estado; problema de escoamento em rede simples	5
QUÍMICA INORGÂNICA	— Estrutura electrónica dos átomos. Tabela periódica — Compostos iónicos; estudo de $ClNa$, NaF, CaF_2; força de ligação e potencial de ionização — Compostos co-valentes; estudo dos halogenetos de C, S, P e N — Metais de transição; formação de complexos de coordenação	5
INTRODUÇÃO À QUÍMICA FÍSICA	— Estados da matéria; tipos de substância; mudanças de estado — Teoria cinética dos gases; equação de Van der Waals; lei dos estados correspondentes — Estrutura molecular e espectroscopia de ultravioleta, infravermelho e raios X	5
		26

SEGUNDO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
ANÁLISE MATEMÁTICA II	— Integração. Integrais duplos e triplos — Séries; critérios de convergência. Determinação da soma de uma série convergente	7
INTRODUÇÃO À ENGENHARIA QUÍMICA	— História e perspectivas futuras para a engenharia química — Conceito de processo químico. Conceito de operação unitária — Breve descrição de equipamento e serviços utilizados em engenharia química — Exemplos de problemas de engenharia química equacionados por métodos numéricos e solúveis por computadores	6
TERMODINÂMICA QUÍMICA I	— Primeira lei da termodinâmica; termoquímica; entalpia — Segunda lei da termodinâmica, ciclo de Carnot; função de entropia — Relações PVT; correlações generalizadas; factor de compressibilidade — Funções de energia livre; critérios de equilíbrio	4
QUÍMICA ORGÂNICA I	— Revisão geral de estrutura e caracterização dos compostos orgânicos: hidrocarbonetos alifáticos; aldeídos e cetonas; aminas e amidos; ácidos carboxílicos — Benzeno; compostos cíclicos e acíclicos. Isomerismo — Efeitos indutivos, de ressonância e estereoquímicos na reactividade das moléculas — Nucleófilos e electrófilos	5
QUÍMICA ANALÍTICA	— Teoria de ácidos e bases; força de ácidos e bases — Actividade e coeficiente de actividade — Oxidação-redução; pilhas — Titulações: ácido base; redox; complexometria — Soluções-tampão — Preparação de soluções; normalidade, molaridade e molalidade — Caracterização das principais reacções dos grupos de elementos	5
		27

SEGUNDO ANO

PRIMEIRO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
ANÁLISE MATEMÁTICA III	— Equações diferenciais; exemplo de como surgem em problemas de engenharia química — Equações diferenciais de primeira ordem. Equações diferenciais de segunda ordem com coeficientes constantes; solução por séries de Taylor — Tipos de equações de derivadas parciais de segunda ordem; sua solução por separação de variáveis.	6
DINÂMICA DE FLUIDOS	— Movimentos laminar e turbulento, número de Reynolds; perfil de velocidades — Balanços macroscópicos e diferenciais — Análise dimensional; aplicação dos balanços macroscópicos à medição de caudais (equação de Bernouilli) — Fluidos newtonianos e não newtonianos, viscosidade — Leis dos movimentos laminar e turbulento — Coeficiente de transferência de momento — Aplicações ao projecto de condutas, bombas, etc.	7
TERMODINÂMICA QUÍMICA II	— Mistura de soluções; quantidades parciais; potencial químico; misturas ideais; misturas líquidas — Equilíbrio químico; sistemas reactivos; afinidade; constante de equilíbrio; mudança de etalpia padrão — Equilíbrio de fase; regra das fases de Gibbs; fugacidade; imiscibilidade; azeótropos; fusão congruente e incongruente	5
QUÍMICA ORGÂNICA II	— Mecanismo de reacções: substituições alifáticas e aromáticas, electrófilas e nucleófilas — Compostos aromáticos heterogéneos; proteínas e carbo-hidratos — Produção de hidrocarbonetos petroquímicos a partir de petróleo e gás natural; processos para a produção em larga escala de produtos químicos orgânicos (incluindo derivados do cloro, oxigénio e azoto) a partir de hidrocarbonetos — Polímeros naturais e sintéticos. Reacções de polimerização e produção industrial de polímeros de adição, poliamidas, poliésteres, elastómeros sintéticos	5
LABORATÓRIOS I	— Trabalhos laboratoriais em pequena escala de aspectos fundamentais da Química Inorgânica, Introdução à Química Física e Química Analítica	4
		27

SEGUNDO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
TRANSFERÊNCIA DE CALOR E MASSA (1. *Transferência de calor*)	— Leis de condução, de convecção e de radiação — Coeficientes de transferência de calor locais e globais; previsão de coeficientes de transferência de calor — Transferência de calor com mudança de fase — Aplicação ao cálculo de permutadores	
(2. *Transferência de massa*)	— Leis de difusão molecular; transferência de massa por convecção — Coeficientes de transferência de massa na fase e na interfase; coeficientes locais e globais — Transferência de massa com reacção química — Analogia entre transferência de calor e massa — Aplicações ao caso de operações unitárias de um andar (absorção, extracção, HETR)	7
QUÍMICA FÍSICA APLICADA	— Electroquímica, condutância e reacções iónicas; célula electroquímica — Equilíbrio de fases; soluções ideais e não ideais — Química-Física das superfícies; viscosidade; tensão de superfície e soluções; efeitos de superfície em pequenas partículas e dispersões. Detergência, emulsificação e lubrificação — Estado sólido e estado líquido	6
ESTATÍSTICA E MÉTODOS NUMÉRICOS DE ENGENHARIA QUÍMICA	— Elementos da teoria das probalidades; distribuição normal, binomial e de Doisson. — Testes de amostragem. Análise simples da variância aplicada a organização de experiências — Métodos numéricos para a solução de equações algébricas. Notação de vector e de matriz. Aplicações computacionais. — Métodos numéricos para a solução de sistemas de equações de balanços de massa e de energia lineares e não lineares. — Aplicações computacionais	6
ELEMENTOS DE PROCESSO QUÍMICO	— Representação gráfica de misturas binárias e ternárias — Análise termodinâmica de diagramas de fases binárias e ternárias. Utilização em métodos de separação	4
LABORATÓRIOS II	— Operações laboratoriais de química orgânica — Fenómenos de transferência; ênfase no contacto com o equipamento habitual do engenheiro químico: válvulas, bombas, medidores de caudal, pressão e temperatura, etc.	4
		27

TERCEIRO ANO

PRIMEIRO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
Reactores Químicos I	— Cinética química: base termodinâmica para a cinética; conceito de equilíbrio dinâmico Reacções simples e múltiplas. Modelos cinéticos. Previsão teórica da ordem de uma reacção — Interpretação de dados de reactores — Reactores simples ideais; reactores descontínuos; reactores tubulares; reactores continuamente agitados (CSTR) — Projecto para reacções simples e múltiplas	7
Operações Unitárias I	— Operações de transferência de massa de contacto descontínuo — Operações de transferência de massa de contacto contínuo — Fluxo de fluidos: bombas; compressores	7
Desenho Industrial	— Convenções; tipos de projecção — Diagrama de fluxos e diagrama de tubagens: descrição e interpretação; métodos para apresentação de dimensões e tolerância — Desenho detalhado de uma operação de processo químico escolhida para o efeito	5
Prática de Engenharia Química I	— Fenómenos de transferência. Determinação de propriedades de transporte: viscosidade, condutividade; coeficiente de transferência de calor e massa, etc. — Operações unitárias. Contacto com equipamento e sua operação	4
Métodos instrumentais de Análise	— Critério a adoptar na escolha do método analítico — Métodos ópticos: espectrofotometria de absorção ultravioleta e visível; turbitimetria; nefelometria e reflectância; colorimetria — Espectrofotometria de absorção de infravermelho — Fotometria de chama — Métodos electroquímicos — Cromatografia — Polarografia	4
		27

SEGUNDO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
CIÊNCIA E TECNOLOGIA DOS MATERIAIS EM ENGENHARIA QUÍMICA	— Estrutura cristalina — Metais e ligas: mecanismos de fortalecimento. Tratamentos térmicos e mecânicos. Soldadura. Distensão e fractura — Electroquímica e corrosão. Passivação. Protecção anódica e catódica. Inibidores. Revestimentos. — Materiais de cerâmica e vidro. Comportamento viscoelástico de altos polímeros amorfos — Mecânica dos materiais: testes de tensão, ductibilidade e fractura. Equação de membrana para corpos de revolução com referência particular a recipiente sob pressão com paredes finas — Cilindro de parede grossa para altas pressões — Mecânica de fractura: crescimento de fissura sob fadiga	5
REACTORES QUÍMICOS II	— Efeitos da pressão e temperatura no projecto de reactores — Cinética de reacções catalíticas. Catalise homogénea e heterogénea. Catalisadores — Reacções fluido-particula; transferência de massa e reacção em sólidos porosos Modelos de reacção fluido-sólido não catalítica — Reactores catalíticos heterogéneos; reactores adiabáticos com enchimento; reactores de leito fluidizado	7
OPERAÇÕES UNITÁRIAS II	— Agitação e mistura — Permutadores de calor — Evaporação; secagem; humidificação — Cristalização	7
ELECTROTECNIA GERAL	— Sistemas de medidas e transmissão de informação. Teoria dos circuitos. Circuitos activos. Electrónica. Circuitos básicos — Sistemas de produção e transporte de energia. Motores e geradores. Transformadores — Sistema de controle automático. Funções de transferência. Estabilidade. Critérios de estabilidade	4
PRÁTICA DE ENGENHARIA QUÍMICA II	— Operações unitárias. Ênfase no estudo do máximo rendimento e apreciação do efeito das variáveis operatórias na eficiência — Reactores. Contacto com diversos tipos de reactores. Análise dos dados de um reactor. (Estudo das variáveis que influenciam a composição do produto de uma reacção. Condições óptimas que permitem atingir um determinado objectivo de produção.)	4
		27

QUARTO ANO

PRIMEIRO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/semana*
Modelos Matemáticos em Engenharia Química	— Descrição de problemas de engenharia química por equações diferenciais ordinárias e parciais Cálculo de diferenças e outros métodos numéricos de soluções. Utilização de computador — Caracterização de superfícies de resposta com múltiplas variáveis. Aplicações a problemas de engenharia química — Introdução à programação; aplicação do método de simplex (entre outros) a problemas de produção em indústrias químicas	6
Controle e Automação	— Revisão e aplicação da transformada de Laplace, desenvolvimento em série de Fourier e de MacLaurin. — Análise dinâmica de sistemas. Função de transferência — Controle proporcional e teorema de desvio final. Introdução aos controles integrais e derivativos; sua importância — Teorema do valor inicial. Anulação do desvio final por meio de um controle integral — Controle antecipado; controle cascata; controle auto-adaptável — Aplicações: colunas de destilação; permutadores de calor; de calor; reactores — Controle analógico e digital directo. Modelos matemáticos. Uso de computadores para simulação dinâmica de processos e para controle de uma instalação industrial	7
Instalação e Serviços Industriais	— Produção de calor. Combustíveis. Calorimetria do vapor de água. Utilização do diagrama de Molier — Tiragem: chaminés e ventiladores — Produção de energia. Turbina a vapor. Turbina a gás — Compressores; compressores volumétricos e turbocompressores. Bombas de vácuo. — Tratamento de águas para utilização industrial; desionização — Refrigeração industrial. Fluidos frigorígenos. Métodos criogénicos	5
Operações Unitárias III	— Peneiração e moagem; transporte de sólidos — Estudo do movimento relativo de sólidos e fluidos: filtração; centrifugação; sedimentação; fluidização	5
Projecto Aberto (seminário)	— O aluno executa ou participa na execução de um trabalho de que se pretende obter uma informação que ainda não é conhecida. Este trabalho poderá integrar-se numa investigação em pequena escala em progresso no departamento	4
		27

SEGUNDO SEMESTRE

Disciplinas	*Principais tópicos*	*Horas/ /semana*
PROJECTO QUÍMICO	— Recolha de informação com ênfase na pesquisa bibliográfica — Escolha do processo de fabrico dentro das várias alternativas possíveis. Viabilidade económica. Elaboração (desenho) de um «flowsheet» de instalação industrial. Estudo detalhado de uma parte do equipamento — Análise de custos. Previsão de despesas. Recursos financeiros. (Estudo matemático da análise de rendibilidade do investimento.) — O aluno desenvolverá o seu trabalho com grande independência mas deverá ter, em princípio, uma reunião quinzenal com o tema do projecto. O tema do projecto será distribuído no início do ano	27

CURSOS DE PÓS-GRADUAÇÃO

Na linha do que anteriormente se expôs, apresentam-se, em seguida, algumas sugestões, não exaustivas, dos cursos de pós-graduação.
Saliente-se que a periodicidade com que os cursos serão oferecidos deverá ser função das disponibilidades do departamento e do interesse que suscitarem.

ANO COMPLEMENTAR (M.Sc.) — 12 meses

I — *Ramos de especialização relacionados com Engenharia Química* (exemplos):

a) «Produção e Gestão»
- — Organização e gestão na Indústria
- — Aspectos económicos de uma unidade industrial
- — Optimização do processo
- — Projecto (de Produção/Gestão)
- — Opções (exemplos):
  - Operações Unitárias
  - Estudo de uma Indústria
  - Segurança e Manutenção
  - Controle Financeiro
  - Marketing
  - Engenharia de Sistema

b) «Projecto e Construção»
- — Teoria do Projecto
- — Técnicas de Organização e Gestão
- — Ciências dos Materiais
- — Projecto (Químico)
- — Opções (exemplos):
  - Operações Unitárias
  - Estruturas
  - Engenharia de Sistemas
  - Controle Automático

c) «Investigação e Desenvolvimento do Processo»
- — Projecto de Investigação
- — Métodos Matemáticos
- — Opções (exemplos):
  - Operações Unitárias
  - Reactores
  - Investigação Operacional

d) «Ciências de Engenharia Química»
- Fenómenos de Transferência
- Operações Unitárias
- Fenómenos de Interfase/Catálise
- Opções (exemplos):
  - Controle Automático
  - Materias sólidos (partículas)
  - Projecto de Investigação Aplicada

II — *Ramos de Tecnologias Secundárias Interdisciplinares* (exemplos):

- Engenharia Bioquímica/Alimentos/Adubos
- Engenharia do Ambiente/Sanitária
- Engenharia Têxtil

CURSOS DE CURTA DURAÇÃO

I — *Reciclagem/Actualização* (exemplos):

- Computação
- Estatística
- Reologia
- Catálise

II — *Temas especializados* (exemplos):

- Energia/Combustíveis
- Óleos/Sabões/Detergentes
- Madeira/Pasta/Papel
- Farmácia/Perfumaria/Corantes
- Polímeros/Plásticos
- Vidro/Cerâmica/Refractários
- Refrigeração/Aquecimento/Ventilação

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