Int. J. Heat Mass Transfer. Vol. 23, pp. 663–666.
Pergamon Press Ltd. 1980. Printed in Great Britain.

EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF THE SPRAYED LIQUID HYDRODYNAMICS IN A SWIRLED FLOW

P. S. KUTS and E. G. TUTOVA
Heat and Mass Transfer Institute, Minsk, U.S.S.R.

(*Received* 4 *May* 1979)

Abstract – The paper presents the results of a complex experimental and analytical investigation of the structure of a one- and two-component flow with tangential liquid supply and axial spraying of the second component. It is shown that the structure of this type of flow allows enhancement of the intercomponent heat and mass transfer.

NOMENCLATURE

L,	air flow rate, m^3/h;
r, R,	radius under consideration and chamber radius, respectively, mm;
u, v, w,	axial, radial, and tangential flow velocity, respectively, m/s;
P,	hydrodynamic pressure, atm;
m,	mass, kg;
F,	midsection, m^2;
v_p,	particle velocity, m/s;
c,	drag coefficient;
ρ,	density, g/m^3;
ν,	kinematic viscosity, m^2/s;
a,	constant for the given chamber radius.

Subscripts

g,	gas;
p,	particle.

INTRODUCTION

ONE OF the effective means of influencing heat and mass transfer in spray drying is the arrangement of swirled flows in the apparatus which create a specific hydrodynamic situation in it [1] and promote an increase in the relative velocities of the flow components (gas and dispersed liquid) and agitation of the flow of suspension.

A new scheme of the vortex spray chamber is suggested (Fig. 1), the essence of which is that two opposing swirled flows are produced in the chamber which rotate in different directions. The chamber is a horizontal tube into which the gas and the heat carrier are supplied tangentially in opposite directions [2]. The gas is lead off from the chamber at its center. By convention, the chamber can be subdivided into three zones. Tangential injection of gas on two sides and formation of countercurrent swirled flows occur in zone 1. Zone 2 is located between the end-face surfaces of the chamber and zone 3, the latter being the region where jets meet. In contrast to the cyclone-type apparatus, backward vortical currents are virtually absent in zone 2.

As is known, interpretation of the complex hydrodynamic situation in cyclone and vortical apparatus is based on representation of the flow as a cylindrical turbulent hollow jet [3] the basic qualitative characteristic of which is the tangential flow velocity.

The tangential velocity field recorded by a thermoanemometer in a one-component flow (Fig. 2) is characterized by the presence of zones of quasi-solid and potential rotation, i.e. the flow structure in the chamber obeys the basic laws which govern the swirled flow of an incompressible liquid [4]. The velocity profile over 80% of the chamber length is governed by the following relation valid at $r/R < 1$

$$v = v_{in}\left[\left(\frac{r}{R}\right)^3 + 0.1\right], \tag{1}$$

where v_{in} is the flow velocity in the inlet channel.

The comparison has been made between the net velocities of the one-component swirled flow and the rectilinear flow.

The degree of nonuniformity was assessed by means of the coefficient

$$\xi = \frac{v_1}{v_2}. \tag{2}$$

The net velocity in the swirled flow, v_1, was determined as a mean-integral value for each section of

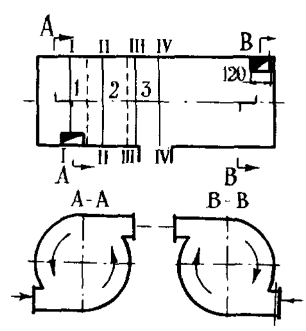

FIG. 1. Schematic of chamber.

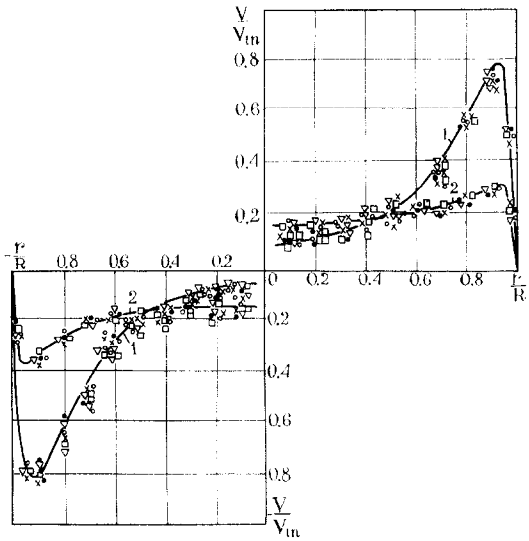

FIG. 2. Distribution of relative velocities in chamber: 1, sections I–III; 2, section IV; ●, $L = 200\ m^3/s$; ×, $300\ m^3/s$; □, $380\ m^3/s$; ○, $440\ m^3/s$; △, $500\ m^3/s$.

Table 1.

L, m^3/h	Sections I–III	IV
200	6.80	5.05
300	6.18	4.70
380	5.95	4.55
440	5.66	4.42
500	5.55	4.27
	$\xi = 6.03$	$\xi = 4.58$

the chamber, while the net velocity of the rectilinear flow, v_2, was determined as a mean value over the chamber cross-section. Table 1 lists the values of ξ as a function of the air flow rate which hardly affects the degree of flow non-uniformity. Comparison of the mean values of the non-uniformity coefficient ξ for different regions of the chamber shows that in zone 3 the non-uniformity degree is diminished by about 30%. Here the zone of quasi-solid rotation is practically absent, which can be attributed to the appearance of local eddies.

It is the high value of the degree of non-uniformity which is the basic advantage of the swirled flow because it leads to enhancement of the interphase exchange.

While the non-uniformity coefficient ξ characterizes the flow in separate chamber sections, the degree of departure of the whole process from the state of equilibrium, which determines its intensity, is characterized by the moving force which corresponds to the type of the apparatus. An experimental study of the apparatus type as to the structure of the flow in it was carried out by the step function technique [5] with the use of a labeled substance (helium) and conventional division of the apparatus into n-pseudo-sections. The analysis of the data (Fig. 3) shows that increase in the flow rate of the labeled substance leads to a change in the number of pseudo-sections of the apparatus, i.e. it characterizes the vortex-type chamber as an apparatus with ideal mixing.

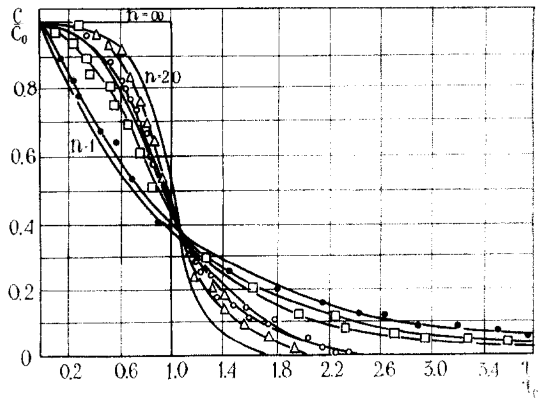

FIG. 3. Comparison of theoretical and experimental curves of the washing-off process. n—1, 20, ∞, experimental curves. △○□●, Labeled substance = 0.57%, 0.75%, 1.29% and 1.52%, respectively.

Apart from determining the type of the apparatus (qualitative picture), the quantitative assessment has been made of the extent to which the moving force is used

$$\varepsilon = \frac{\Delta x_a}{\Delta x_d}, \tag{3}$$

where Δx_d is the moving force in the apparatus with ideal displacement, and Δx_a is the moving force in the actual apparatus.

In the present case $\varepsilon = 0.7$–0.8, which confirms that the classification of the apparatus is correct [6].

The analytical study of the hydrodynamic conditions in the apparatus with a one-component flow is based on the occurrence of a forced vortex ('tangential nozzle') in the entry section. Assuming that the flow is isothermal and the fluid properties are constant, we shall use an axisymmetric system composed of the Navier–Stokes and continuity equations

$$v\frac{\partial v}{\partial r} + u\frac{\partial v}{\partial x} - \frac{w^2}{r} = -\frac{\partial P}{\partial r} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial r^2} + \frac{\partial^2 v}{\partial x^2} + \frac{1}{r}\frac{\partial v}{\partial r} - \frac{v}{r^2}\right), \tag{4}$$

$$v\frac{\partial u}{\partial r} + u\frac{\partial u}{\partial x} = -\frac{\partial P}{\partial x} + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial r^2} + \frac{\partial^2 u}{\partial x^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right), \tag{5}$$

$$v\frac{\partial w}{\partial r} + u\frac{\partial w}{\partial x} + \frac{wv}{r} = \frac{1}{Re}\left(\frac{\partial^2 w}{\partial r^2} + \frac{\partial^2 w}{\partial x^2} + \frac{1}{r}\frac{\partial w}{\partial r} - \frac{w}{r^2}\right) \tag{6}$$

$$\frac{\partial}{\partial r}(rv) + \frac{\partial}{\partial x}(ru) = 0. \tag{7}$$

Here x and r stands for the distances measured from the wall along the axis of symmetry and from the chamber axis in the radial direction, respectively. In the initial system of equations (4)–(7), x and r are normalized with the aid of $R, v, w, u - v_{in}, P - \rho v_{in}^2$ and the number Re is determined as $\mathrm{Re} = (v_{in}R)/\nu$. Then, r and x change within the ranges $0 \leqslant r \leqslant 1, 0 \leqslant x \leqslant x_0$, while the 'tangential nozzle' is located in the subregion $x_v \leqslant x \leqslant x_p$.

The mean velocity distribution over the inlet nozzle length is assumed uniform over the chamber generatrix

$$u = \cos \varphi_x,$$
$$v = -\cos \varphi_r, \quad (8)$$
$$w = \varepsilon_w,$$

where φ_x and φ_r are the parameters which characterize the swirling of the flow and which are determined depending on the type of the apparatus [7].

After suitable transformations of the system of equations with account for the boundary conditions of the given model of a swirled flow, we solve the system of equations (4)–(7) numerically using the method of establishing [8].

Figure 4 presents the profiles of the tangential velocity. The analysis of the curves shows that the circumferential maximum of the velocity degenerates under the influence of viscous friction. However, the primary pattern of the curve coincides with the experimental data of Fig. 2.

The study of the structure of the torch of a liquid sprayed into a swirled flow was carried out in a test facility allowing for the process visualization and its photorecording in a wide range of the parameters of interacting flows [9]. To a certain extent the experimental data make it possible to qualitatively and quantitatively characterize the structure and basic parameters of the torch. The effect of the process hydrodynamics on the time of motion of particles in the chamber volume is graphically illustrated in Fig. 5.

The analysis of the relation

$$\tau_x/\tau_0 = f(R_x/l_x)$$

indicates that the velocity of the swirled flow, and hence the flow structure in the chamber, are dominating in duration of particle transport. A qualitative picture of the transport of particles is determined by the initial impulse (pressure of the compressed air which atomizes the liquid) and by the chamber design parameters. Quantitatively, the position of separate

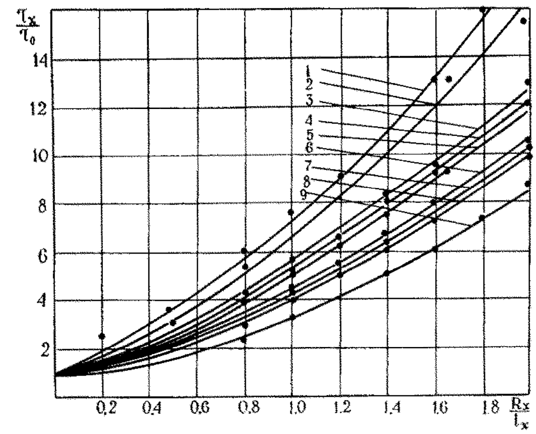

FIG. 5. Effect of the hydrodynamic conditions on the time of transport of particles. τ_x, time required for drops to move from the spouter nozzle out to the prescribed point; τ_0, the same but in axial direction; R_x, radius under consideration; l_x, distance along the axis up to the prescribed radial location. 1–3, P = 3.2 atm; 4–6, 2.2 atm; 7–9, 1.5 atm; 1, 4, 7, v_{in} = 30 m/s; 2, 5, 8, 20 m/s; 3, 6, 9, 10 m/s.

particles, and consequently, of the whole drop suspension flow, depends on the velocity of the swirled flow (v_{in}). It should be noted that the path covered by particles is not proportional to the air flow velocities. Thus, an increase in the velocity up to 30 m/s is not advisable, since the backward currents forming in this case cancel the intensifying effect of the velocity. The analysis of the data allows one to substantiate the choice of the optimal hydrodynamic conditions for a dispersed jet in swirled flows and the design parameters of the chamber.

The trajectory of single particles in a swirled flow calculated by the numerical method [10] from the equation

$$m\frac{\mathrm{d}v_p}{\mathrm{d}\tau} = -\frac{c\rho F}{2}|v_p - v|(v_p - v), \quad (9)$$

is given in Fig. 6. It is natural that the higher the angular velocity, determined by the tangential component

$$w = v_{p\varphi/r},$$

the quicker the chamber wall is reached by a particle.

In order to analyze the hydrodynamics of meeting of

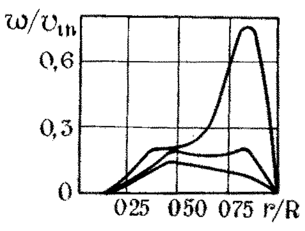

FIG. 4. Profile of the tangential velocity component in sections $x_{\text{I–III}}$ = 0.5, 1.0, 1.4, respectively.

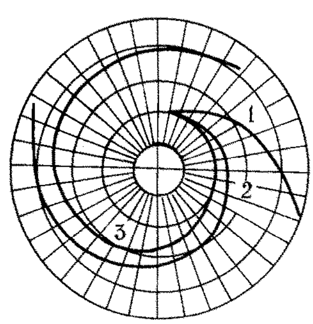

FIG. 6. Trajectory of particles. Angular velocities: (1) 45 rad/s; (2) 30 rad/s; (3) 20 rad/s.

jets (swirled flows in the center of the chamber) it is possible to limit the discussion by the motion of separate particles. As is known, when the jets collide, a solid particle experiences multiple decaying vibrational displacements.

Equation (9), with account for the basic concepts of the theory of jet impingement onto the wall [11], allowed determination of the maximum depth of particle penetration into the incoming jet (z_{max}) and a maximum deviation of the particle trajectory in the tangential direction (φ_{max}) [12]. Thus, for the transitional region we have

$$\varphi_{max} = 0.0245\frac{1}{r}\frac{d^{1.5}\rho_p}{\nu^{0.5}\rho_g}\left(\frac{a^2}{a^2+1}\right)^{1/4}\sqrt{(v_{g\varphi})} \quad (10)$$

$$z_{max} = 0.245\frac{d^{1.5}v_p\sqrt{(v_{pz})}}{\nu^{0.5}\rho_g(a^2+1)^{1/4}}. \quad (11)$$

The predicted results are confirmed rather satisfactorily by experiment. The maximum path of retardation fluctuates within 0.01–0.11 m for liquid drops of 100–1000 μm in size.

The study of the hydrodynamics of the opposite swirled flows of dispersed particles makes it possible to elucidate the mechanism underlying enhancement of the interphase heat and mass transfer, for example, in the process of spray drying, and to suggest the method of calculation of the apparatus.

REFERENCES

1. A. P. Merkulov, *Vortex Effect and Its Application in Technology*. Izd. Mashinostroenie, Moscow (1960).
2. P. S. Kuts and E. G. Tutova, Authors' Certificate No. 453543, *Invent. Bull.* **46** (1974).
3. P. S. Kuts, E. G. Tutova and G. S. Kabaldin, Study of the aerodynamics of a vortex spray drier, *J. Engng Phys.* **24** (4), 708–714 (1973).
4. L. A. Vulis and B. A. Ustimenko, Concerning aerodynamics of a cyclone furnace chamber, *Teploénergetika* **9**, 3–10 (1954).
5. P. S. Kuts, E. G. Tutova, V. I. Rubezhansky and V. A. Zavadsky, Experimental determination of the extent of use of the moving force in a vortical spray dryer, in *Thermophysics and Technology of Drying-Thermal Processes*, pp. 170–176. Izd. ITMO AN BSSR, Minsk (1975).
6. A. N. Planovsky, V. M. Ramm and S. Z. Kagan, *Processes and Apparatus of Chemical Technology*. Izd. Khimiya, Moscow (1968).
7. V. A. Dolgushev and G. S. Kabaldin, On the characteristics of swirled flows, in *Thermophysics and Technology of Drying-Thermal Processes*, pp. 106–109. Izd. ITMO AN BSSR, Minsk (1975).
8. P. S. Kuts and V. A. Dolgushev, Numerical investigation of tangential swirling of jets of a viscous incompressible liquid, *J. Engng Phys.* **30**(6), 1047–1054 (1976).
9. V. A. Zavadsky, E. G. Tutova and T. L. Fyodorova, Study of the torch of a liquid dispersed into a swirled flow, in *Problems of Drying and Heat Treatment*, pp. 193–200. Izd. ITMO AN BSSR, Minsk (1976).
10. P. S. Kuts and N. N. Grinchik, Numerical study of the motion of variable-mass particles in a vortex flow, *Proceedings of the 5th All-Union Heat and Mass Transfer Conference* Vol. 5, pp. 221–230. Izd. ITMO AN BSSR, Minsk (1976).
11. Bai-Shi-I, *Theory of Jets*. Fizmatizdat, Moscow (1960).
12. P. S. Kuts, E. G. Tutova, N. N. Grinchik and V. A. Zavadsky, Study of the motion of particles in the region of meeting of swirled jets, *J. Engng Phys.* **30**(2), 228–234 (1976).

RECHERCHE EXPERIMENTALE ET THEORIQUE SUR L'HYDRODYNAMIQUE D'UN LIQUIDE EN BROUILLARD DANS UN ECOULEMENT TOURBILLONNAIRE

Résumé—On présente les résultats d'une étude complexe expérimentale et théorique sur la structure d'un écoulement à un et deux composants avec alimentation tangentielle de liquide et dispersion axiale du second composant. On montre que la structure de ce type d'écoulement provoque l'accroissement simultáné du transfert de chaleur et de masse.

EXPERIMENTELLE UND ANALYTISCHE UNTERSUCHUNG DER HYDRODYNAMIK EINER IN EINE WIRBELSTRÖMUNG EINGESPRITZTEN FLÜSSIGKEIT

Zusammenfassung—In der Arbeit werden Ergebnisse einer umfassenden experimentellen und analytischen Untersuchung über die Struktur einer Ein- und Zweikomponentenströmung mit tangentialer Flüssigkeitseinspeisung und axialer Einspritzung der zweiten Komponente mitgeteilt. Es wird gezeigt, daß die Struktur dieser Strömungsart eine Erhöhung des Wärme- und Stoffübergangs zwischen den Komponenten zuläßt.

ЭКСПЕРИМЕНТАЛЬНОЕ И АНАЛИТИЧЕСКОЕ ИССЛЕДОВАНИЕ ГИДРОДИНАМИКИ РАСПЫЛЕННОЙ ЖИДКОСТИ В ЗАКРУЧЕННОМ ПОТОКЕ

Аннотация — В статье изложены материалы комплексного экспериментального и аналитического исследования структуры одно- и двукомпонентного потока при тангенциальном подводе жидкости и осевом распыле второго компонента. Показано, что структура потоков подобного типа позволяет интенсифицировать межкомпонентный обмен.