Int. J. Heat Mass Transfer. Vol. 9, pp. 427–432. Pergamon Press 1966. Printed in Great Britain

ON THE HYDRAULIC RESISTANCE AND FLOW STRUCTURE OF A GAS–LIQUID MIXTURE IN AN ANNULAR PASSAGE WITH A ROTATING CYLINDER INSIDE

E. G. LEONOV*, Yu. P. FINATIEV† and B. S. FILATOV*

(*Received* 2 *April* 1965)

Аннотация—Сообщаются результаты визуального исследования структуры двухфазного потока при дисперсном и пробковом течениях, а также приводятся данные о влиянии вращения внутреннего цилиндра на гидравлическое сопротивление и истинное газосодержание в кольцевом канале.

Установлено, что в исследованном авторами диапазоне изменения числа Рейнольдса смеси, истинного газосодержания и скорости вращения внутреннего цилиндра, вращение не приводит к существенному изменению структуры течения и истинного газосодержания, но вызывает существенное увеличение гидравлического сопротивления кольцевого канала.

NOMENCLATURE

Re_{cm}, $= (1-\varphi)\dfrac{2v_1(r_2-r_1)}{\nu_1} + \dfrac{2\varphi\, v_2(r_2-r_1)}{\nu_2}$, the Reynolds number of mixture;

ν_1, ν_2, kinematic viscosity of water and air;

r_1, r_2, radii of internal and external cylinders;

g, gravitational acceleration;

v_1, $= \dfrac{G_1}{\gamma_1 F(1-\varphi)}$, mean velocity of water;

v_2, $= \dfrac{G_2}{\gamma_2 F\varphi}$, mean velocity of air;

v_{cm}, $= v_1 - \varphi(v_2 - v_1)$, mean velocity of mixture;

Fr_{cm}, $= \dfrac{v_{cm}^2}{2g(r_2-r_1)}$, the Froude number of mixture;

β, volume gas content equal to the ratio of the volume of gas flow to the volume of mixture flow;

G_1, G_2, water and air weight flow rates;

η, $= \dfrac{\gamma_2\,\beta}{\gamma_p}$, gas content by weight in flow;

γ_1, γ_2, specific weights of water and air;

γ_p, $= \gamma_1 - \beta(\gamma_1 - \gamma_2)$, specific weight of mixture in flow;

v_φ, $= \dfrac{2\pi\, r_1\, n}{60}$, circumferential velocity of internal cylinder rotation;

$\lambda(Re_{cm})$, coefficient of hydraulic resistance for the flow of one of the phases of the mixture with Re equal to Re of the mixture;

λ_{cm}, hydraulic resistance of the passage to the flow of mixture;

ψ, $= \dfrac{\lambda_{cm}}{\lambda(Re_{cm})}$, relative resistance;

$\bar{\mu}$, phase viscosity ratio;

j, phase specific weights ratio;

φ, true volume gas content equal to the ratio of the area occupied by gas to the total area of annulus cross-section.

* Oil Chemistry and Gas Industry Institute, Moscow.
† Institute of Mechanics, USSR Academy of Sciences, Moscow.

THE investigations of flow of gas-mixtures through passages of various shapes are of great scientific value and of practical importance.

At present a large number of works relating to this subject is available.

At this time great interest is being shown in the study of gas–liquid flow dynamics in an annular passage formed by concentrical tubes, but the number of works dealing with this problem is small. The situation is even worse with regard to the investigations of flow processes of gas–liquid mixtures in annular passages with a rotating internal cylinder.

In some instances it appears necessary to determine the friction losses in the annulus with a rotating internal cylinder for the flows of a gas–liquid mixture, in particular, an air–water mixture.

As far as we know, no results of this sort are available in print or from other sources.

From the experimental and theoretical investigations [8–10] of turbulent flow in smooth annular passages with a rotating internal cylinder, one would expect that in the case of a two-phase mixture flow, the rotation of the internal cylinder would produce an increase in the hydraulic resistance of the channel.

In this connection it is not clear whether the influences of the centrifugal effect and that of the tangential friction forces are identical in the cases of single and two-phase flows. It is rather difficult to answer this question without an experiment since, to begin with, we have no clear idea of the local structure of the two-phase flow in the cross-section of the passage.

For the above reasons we began the experimental study of this kind of flow.

Experiments show [7] that, in an annular passage with axial flow of liquid and rotation of the internal cylinder, the flow has a rather complicated structure. This becomes even more complicated in the presence of the gas phase.

In the present paper, data are reported of experimental studies of the hydraulic resistance in a vertical annular passage with a rotating cylinder and ascending flow of an air–water mixture over the range of variations of the rotational speed n from 0 to 500 rev/min, the true volume gas content φ from 0·0 to 0·35, and $Fr_{cm} = 5$ to 20, with the pressure in the passage of 1·2 kg/cm^2, and $Re_{cm} = 10^4$.

In the apparatus employed an annular gap was formed between an internal rotating metal cylinder and an external stationary tube made of transparent plastic. The external diameter of the inner cylinder was 88 mm, the internal one of the outer cylinder, 116 mm. The total length of the passage with entrance region was 1250 mm.

To carry out visual investigations, the inner cylinder was covered with black varnish, and the outer one was carefully polished. The relative roughness of the surfaces in the working annular passage was $r_1/K = 10000$ to 12000.

A special chamber was provided to ensure uniform water supply to the annular passage, which was vertical, and the flow was upwards.

The liquid was circulated by means of a rotary pump rated 3 l/s. The steady supply of water to the annular passage was provided by a constant level tank.

At the inlet to the working section were mounted a mixer and a ring made of a length of brass tube with twelve unions through which air was supplied to the liquid. This arrangement provided uniform supply of air over the whole circumference of the annular passage.

Holes for static pressure tappings were made every 100 mm along the outer cylinder.

The distribution of the static pressure along the passage length was measured by an inclined multi-tube manometer, the water flow was obtained by weighing, and that of the air, by means of a flowmeter; the rotational speed of the inner cylinder was measured by a hand tachometer, the temperature of water at the inlet and outlet of the working section was controlled by mercury thermometers. In a study of two-phase flows the measurement of static pressure is particularly difficult, because of the large pressure fluctuations which may exceed the static pressure drop.

To prevent this, special compensation bulbs made of transparent plastic were used for visual observation of degassing of the liquid flowing into the manometer. Also small bore supply hoses were employed. All this provided large damping of the pressure tappings system and allowed sufficiently accurate measurements of the frictional losses.

The true gas content was determined by the use of gamma-raying [3–5]. This method allowed the mean values of the true gas content to be found for any place in the working section. For this purpose a special device was designed with thallium-203 as an isotope. Gamma-raying was performed on the hydrodynamically stabilized section both with and without rotation of the internal cylinder over the whole area of the passage cross-section.

Before studying the influence of rotation of the internal cylinder upon the hydraulic resistance and true gas content in the annular passage, we first investigated the hydraulic resistance in the annular passage and evaluated the true gas content when the walls were stationary.

Certain common laws were established for the flows of gas–liquid mixtures in circular tubes and in annular passages.

It was found that, within the range of the experimental accuracy (approx. 10–15 per cent), for a gas–liquid mixture the hydraulic resistance in an annular passage was equal to that in a circular tube of an equivalent diameter.

In the study of the hydrodynamics of two-phase flow the main problem was to find the dependence of the resistance coefficient λ_{cm} and the true gas content φ on a number of dimensionless parameters.

Teletov [1, 2] established first the general differential equations describing the hydrodynamics of two-phase mixtures, and on these bases derived dimensionless similarity numbers for such flows. He also proposed a more fundamental method for the treatment of experimental data in the following form:

$$\frac{\lambda_{cm}}{\lambda(Re_{cm})} = \psi(\beta, Fr_{cm}, \bar{\mu}, j \ldots \text{etc.})$$

The aim of the present study was to determine the influence of the rotation of the inner cylinder on the true gas content, the hydraulic resistance and the structure of the mixture flow. By analogy with the one-phase flow under similar conditions [7–9] one can suppose that again the twist coefficient v_φ/v_{cm}, i.e. the ratio of the rotational speed of the internal cylinder to the axial flow rate of the mixture, will be the dimensionless parameter upon which depend the unknown values, other parameters being constant.

In the experiments, the authors sought to keep Re_{cm}, $\bar{\mu}$, Fr_{cm} and j, while the rotational speed v_φ of the internal cylinder was varied.

The study of the influence of the rotation of the internal cylinder on the hydraulic resistance, structure and true gas content was carried out in the following way.

First, a steady-state flow regime of the mixture with the given values v_{cm} and φ was produced in the test section of the apparatus while the inner cylinder remained stationary.

The desired values of v_{cm} and φ were set by adjusting the water and air flows. The pressure drops ΔP were measured along the working section L and the structure of the flow was ciné-photographed. Next the inner cylinder was rotated with the required circumferential speed v_φ, φ and ΔP_φ were measured again and the flow structure in the field of centrifugal forces was recorded. It appeared impossible to find any significant influence of the rotation upon the true gas content within the studied range of variations of φ and rotational speed v_φ. Only a slight increase, no higher than 10–15 per cent, was observed with the increase of the rotational speed, as can be seen in Figs. 1 and 3.

This fact leads one to think that the structure of the gas–liquid flow did not suffer any substantial changes either.

This conclusion is supported by the visual observations and filming of the flow structure carried out by the present authors. The flow patterns of a gas–liquid mixture, in dispersed and slug flow, which are most typical in practice have been studied.

In Fig. 2 positions 1 and 2 refer to a dispersed

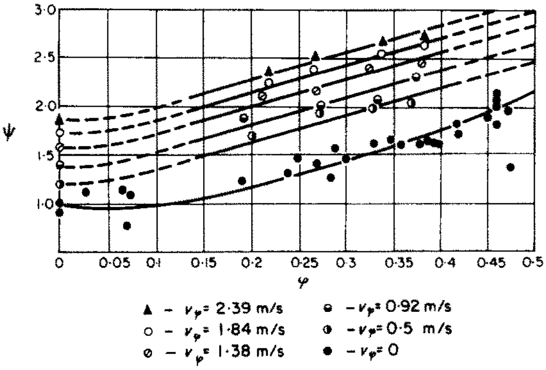

FIG. 1. The influence of rotation of the internal cylinder upon the related coefficient of resistance with different true volume gas contents.

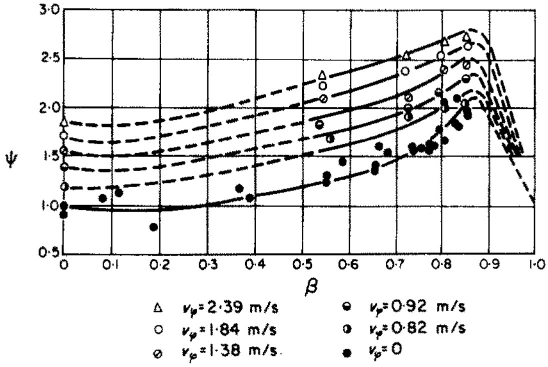

FIG. 3. The influence of rotation of the internal cylinder upon the related coefficient of resistance in an annulus with different volume gas contents in the flow.

flow at $n = 0$ and $n = 500$ rev/min, respectively, and positions 3 and 4 to a slug flow at $n = 0$ and $n = 500$ rev/min.

The examination of these pictures confirms the conclusion that there is a slight influence of rotation upon the structure of the two-phase flow within the range of variations of φ from 0 to 0·35 and n from 0 to 500 rev/min, at $r_1/r_2 = 0{\cdot}758$. However, it should be mentioned that in one-phase flows with a certain ratio v_φ/v (v is the one-phase flow rate) Taylor vortices [6, 7] are formed in a gap. These have right- and left-hand rotations and their circulation axes lie in the planes perpendicular to the axis of the annulus. (Fig. 2, position 5.)

The question arises whether the onset of Taylor vortices is possible in a gas–liquid mixture flow. This question is of practical importance for a number of technological processes (separation, centrifuging, etc.). It was found that in a dispersed regime when $v_\varphi/v_{cm} > 5$ Taylor vortices were also formed in the flow. In that case the air phase concentrated in the regions between the vortices where the velocities on the periphery of the vortices were directed towards the walls of the external cylinder. The visual picture of the air distribution between the Taylor vortices is shown in Fig. 2, position 6.

The results of the experimental study of the hydraulic resistance in the annular passage with the rotating inner cylinder are shown in Figs. 1, 3 and 4.

Rotation of the inner cylinder led to an increase of the hydraulic resistance. But its dependence upon the rotational speed remained

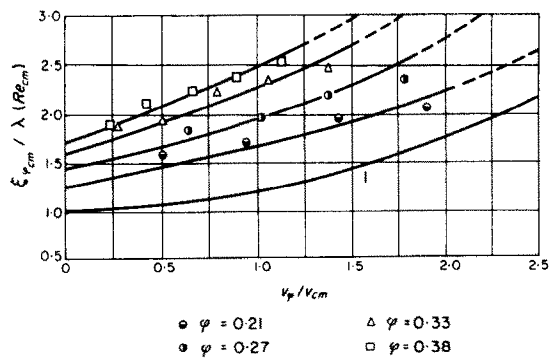

FIG. 4. Ratio of resistance coefficients $\xi_{\varphi_{cm}}/\lambda(Re_{cm})$ vs. the speed of rotation of the internal cylinder rotation with various gas contents.
1. according to [8] and [10] $\varphi = 0$ in homogeneous liquid flow.

almost similar to that of the case of the cylinder rotation in one-phase medium. In Fig. 1 the co-ordinates $\psi = f(\varphi)$ represent the dependence of the related resistance coefficient upon the speed of the inner cylinder rotation. In this figure the lowest curve corresponds to the zero speed of rotation. The experimental points above correspond to various rotational speeds of the

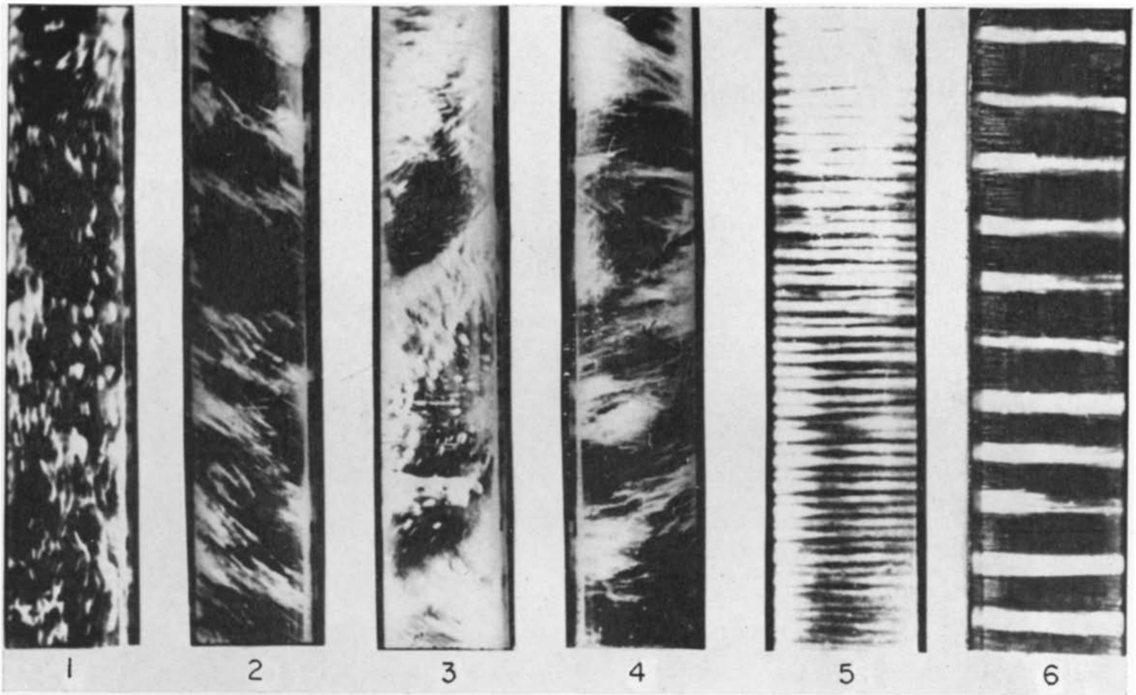

FIG. 2. Structure of gas–liquid mixture flow in an annulus.
1. Dispersed flow at $n = 0$.
2. Dispersed flow at $n = 500$ rev/min.
3. Slug flow regime at $n = 0$.
4. Slug flow regime at $n = 500.$ rev/min.
5. One-phase flow with Taylor vortices.
6. Gas–liquid mixture flow with Taylor vortices.
at $Re_{\varphi} = 8 \times 10^4$; $Re_{cm} = 10^4$.

inner cylinder. As it can be seen from this picture, the hydraulic resistance increases with the increase of the rotational speed. The curves connecting the points corresponding to v_φ = const. are equidistant from the curve for $\varphi = 0$, which shows the similarity of laws of flow in both cases. In Fig. 3 the graph plotted as $\psi = f(\beta)$ proves the same. In other words, no specific influence was found of the rotation upon the two-phase flow in contrast to the case of one-phase flow, within the studied range of variations of gas content and rotational speed. It therefore can be expected that the dependence of resistance on the rotational speed of the inner cylinder in a gas–liquid flow will be similar to that for one-phase flow.

In Fig. 4 are plotted the values of the ratio of the coefficient $\xi_{\varphi_{cm}}$ of the annulus resistance to the flow of the gas–liquid mixture with a rotating inner cylinder, to the coefficient $\lambda(Re_{cm})$ of the same annulus to the homogeneous flow along the axis without rotation, versus the so-called twist coefficient v_φ/v_{cm}.

$$\frac{\xi_{\varphi_{cm}}}{\lambda(Re_{cm})} = f\left(\frac{v_\varphi}{v_{cm}}\right)$$

The value $\xi_{\varphi_{cm}}$ can be expressed as follows:

$$\xi_{\varphi_{cm}} = \frac{2\Delta P_\varphi}{\gamma_p H} \Big/ Fr_{cm}\left[\eta\frac{\beta}{\varphi} + (1-\eta)\frac{1-\beta}{1-\varphi}\right]$$

The graph in Fig. 4 can be used to estimate the influence of the internal cylinder rotation upon the coefficient of the hydraulic resistance in the annulus with gas–liquid mixture flow, within the studied range of variation of the parameters.

The investigations were carried out for one value of $r_1/r_2 = 0{\cdot}758$ only. This occurs often in a number of branches of industry (oil and chemicals).

Can one consider these conclusions valid for other values of r_1/r_2 which are different from the one studied? It is difficult to answer this question at present without further experimental studies. However, it may be inferred from the study of the gap-size effect in the one-phase flow that the authors' conclusions remain valid within a fairly wide range, i.e. $0{\cdot}5 < r_1/r_2 < 0{\cdot}8$.

REFERENCES

1. S. G. TELETOV, Hydrodynamics of two-phase fluids, Doctoral thesis, Moscow State University (1949).
2. S. G. TELETOV, Equations of hydrodynamics of two-phase fluids, *Dokl. Akad. Nauk SSSR* **50**, 99–102 (1945).
3. Z. L. MIROPOLSKY and M. A. STYRIKOVICH, The use of gamma-rays for the study of hydrodynamics of two-phase systems, *Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk* No. 9, 154–159 (1955).
4. L. S. STERMAN and A. V. SURNOV, The use of gamma-rays for determination of differential volume vapour content and true level in the apparatus, *Teploenergetika* No. 8, 39–42 (1955).
5. S. I. KOSTERIN, V. V. POLYAKOV, N. I. SEMENOV and A. A. TOCHIGIN, Hydraulic resistance of steam–water flows in vertical unheated pipes, *Inzh.-Fiz. Zh.* No. 7, 3–10 (1962).
6. G. TAYLOR, Stability of a viscous liquid contained between two rotating cylinders, *Proc. R. Soc.* **A223**, 289 (1923).
7. S. I. KOSTERIN and YU. P. FINATIEV, On the structure of the turbulent flow in an annular channel with a rotating internal cylinder, *Inzh.-Fiz. Zh.* 96–101 (1963).
8. S. I. KOSTERIN and YU. P. FINATIEV, Hydrodynamics and heat transfer of a gas flow between rotating cylinders, in the collected articles *Heat Transfer and Cooling of Electric Machines*, pp. 3–15. Elektroprom, Moscow (1963).
9. YU. A. KOSHMAROV, The hydrodynamics and heat in the gap between rotating coaxial cylinders, *Inzh.-Fiz. Zh.* No. 5, 5–15 (1962).
10. R. I. CORNISH, Flow of water through fine clearances with relative motion of the boundaries, *Proc. R. Soc.* **A140**, 223–240 (1933).

Abstract—The results of visual investigation are reported for two-phase dispersed and slug flows, and the data are given on the influence of the inner cylinder rotation upon the hydraulic resistance and true gas content in an annular passage.

It was found that within the range of the mixture *Re* numbers studied, the true gas contents and the rotational speeds of the inner cylinder, the rotation does not significantly change the flow structure and the gas content, but it does raise substantially the hydraulic resistance in the annulus.

Résumé—Les résultats d'une étude visuelle pour les écoulements diphasiques dispersés et en bloc sont exposés ainsi que ceux donnant l'influence de la rotation du cylindre intérieur sur la perte de charge et la véritable proportion de gaz dans une conduite annulaire.

On a trouvé que dans la gamme étudiée des nombres de Reynolds du mélange, des véritables proportions de gaz et des vitesses de rotation du cylindre intérieur, la rotation ne change pas d'une façon sensible la structure de l'écoulement et la proportion de gaz, mais augmente d'une façon importante la perte de charge dans la conduite annulaire.

Zusammenfassung—Für die Strömung zweier Phasen in vermischter Form oder als Kolbenströmung werden die Ergebnisse einer visuellen Untersuchung mitgeteilt. Der Einfluss auf den hydraulischen Widerstand infolge der Rotation des inneren Zylinders und des wahren Gasgehalts im Ringraum ist angegeben.

Es zeigte sich, dass im Bereich der untersuchten Reynolds-Zahlen des Gemisches, des wahren Gasgehalts und der Rotationsgeschwindigkeiten des Innenzylinders die Strömungsstruktur und der Gasgehalt durch die Rotation nicht merklich verändert werden, der hydraulische Widerstand im Ringspalt sich aber beträchtlich erhöht.