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To cite this article: A A Kishkin et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 255 012013

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Investigation of swirling diphasic flow in centrifugal phase separator

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Abstract. Separation of disphasic mediums form the basis of many technological processes. However calculation methods for diphasic mediums used in industry found on empirical studies and cannot lay a claim to universality. In the offered model of swirling diphasic flow the flow is divided into the viscous interface and the diphasic core. To research the flow of liquid in the area of the viscous interface with big gradients of velocity Navier-Stokes equations are used.

The analysis of the existing methods to separate gas-liquid mixtures shows that in the basis of phase separation the density heterogeneousness of the diphasic flow is used efficiently.

In the constant gravity environment the density heterogeneousness of the resting liquid is the source of Archimedean force influencing particularly gas bubbles and making them float to the free surface.

If body forces spring up as the result of the liquid movement, then their values and directions depend upon distribution of the velocities in the flow and eventually are defined by pressure forces and viscosity forces. In such an environment with the liquid movement in curvilinear channels and with flow swirling caused by the swirler in the tubes internal inertial forces spring up.

Otherwise inertial forces in moving systems (channels) spring up. In this case inertial forces are external to the moving flow and will be defined by the environment of the system movement not by the flow. Inertial forces springing up with the system spinning in its accelerated or slowed-down movement would belong to this category.

The usage of centrifugal inertial forces phase separating devices implies creation of the area with the swirled sheeted diphasic flow. With all that the centrifugal force field can be both external and internal to the flow. In the first case the body forces will be defined by the parameters of the spinning system concerned with the flow and entirely depend upon it. In the second case the level of inertial forces will definitely concern with the forces causing forced movement.

The first variant is realized in the devices of rotary type that have mechanical drive with the available power of the shaft. In the second case the spin is carried out by special devices that can be subdivided into three types: screw inserts, tangential channels and spade swirlers.

In different fields of industry centrifugal separators (phase separators, cyclones, hydrocyclones) are applied to separate gas-liquid systems. They are remarkable for simplicity of construction, great carrying capacity, low materials consumption, being easy in use and high performance.
The mechanical method of phase separation is most economizing particularly in degasation in the field of centrifugal forces. In this connection the devices of hydrocyclone type have recently got their new application. They have come to be used to refine liquids from dissolved and dispersed gases. With the rise of technological demands of gas content of liquids new hydrocyclone constructions have been designed. They make it possible to provide effective phase separation in each definite case.

Centrifugal separation of gas-liquid mediums is remarkable for high performance and is widely used in heat exchange and mass transfer equipment. Centrifugal phase separator of various types have become widely spread.

Schematically the construction of centrifugal phase separator (fig. 1) can be presented in the following details:
- diphasic mixture supply (1);
- device to transform entrance axial flow into the swirled one (the swirler) (2);
- swirling chamber (3);
- circumferential pipe-bend of the gas phase (4);
- central (axial) pipe-bend of the gas phase (5).

Separation of diphasic flow is based on the fact that in the centrifugal field there is separation force that influences gas insertions in the liquid and shifts them to the axis of the chamber. In the centre of the chamber there springs up a gas vortex squeezed by the liquid ring. The separated swirled flow is moving towards the axis, at the outlet of the chamber diverting of separated phases is carried out.

Pilot researches of degasation of gassy liquid in the phase separator showed that velocity enhancing of the liquid flow in the inlet of the device ambiguously influences efficiency of the device. For gassy liquids velocity enhancing raises efficiency but within the definite scope. Getting some certain value of the liquid velocity in the inlet of the hydrocyclone increases drag-out of gas bubbles in outgoing flow of the liquid. In this case gas bubbles do not manage to enter the central zone of the phase separator.
Stability of gas-liquid mixture is very largely defined by dispersity of the gas in the liquid. However even with high gas dispersity noticeable phase separation happens in a fraction of a minute.

The main factors to define characteristics for the course of the swirled flow are:
- geometry of continuous-flow part of the chamber in the phase separator;
- regime parameters (consumption of operational liquid and gas);
- characteristics of operational liquid (density, viscosity, temperature);
- characteristics of gas (density, temperature);

The valid obstacle in projecting is the fact that centrifugal phase separators in spite of being widely spread are still very little studied both experimentally and theoretically. It is explained by complexity of running fine model researches at pilot plants.

Lack of information about the processes that really take place during separation of diphasic mixtures blocks development of theory and engineering designs and can be compensated by proper analysis of hydrodynamics equations of swirled flows and designing on its basis a mathematical model for the process of mixtures phase separation.

The basis of diphasic flow theory exists in classic mechanics of liquid and gas and explains in details movement of each phase. However its up-to-date condition is so that applying strict conclusions from fundamental correlations such as Navier-Stokes equations is not possible because calculations of diphasic flows are not reliable. The combination of the factors that cause all this is the following: endless variety of geometric forms of interphase area and flow regimes, great influence of small quantities of admixtures and small changes of geometry.

There are several methods to analyse diphasic flows.

The first approach is descriptive and experimental. It rests on empirical correlation. The method of correlation is the simplest form of analysis where regularities in behavior of experimental data are conveyed numerically, mostly with the help of dimensionless, physically valid complexes. However derivable regularities are applicable only for a very narrow scope of changeable parameters.

One of theoretical methods is a model of homogeneous flow. The real diphasic flow is a flow divided into areas with essentially different characteristics. Homogeneous theory of diphasic flows is a kind of try to present a flow as a monophasic one [1]. Such approximation begets mistakes that are corrected by involving supplementary members or coefficients in calculation equations.

In the model of separated flow [2] (sometimes it is called a model or theory of heterogeneous flow) each phase has its own characteristics (temperature, density, velocity) and should correspond to some form of normal laws of conservation of mass, impulse, energy.

The most well-grounded approach to the analysis of diphasic flow includes consideration of each phase as a continued medium and getting detailed description of three-dimensional field of flow. It may rest, for example, on use of two systems of vector equations of continuity and quantity of movement (for example, Navier-Stokes equations) together with boundary conditions and conditions of interphase area including mass carry effect and surface tension. Even if the form of all interphase areas is known (which usually never happens), in all cases except for few special cases, the solution of the problem takes great efforts.

In derivation of conservation equations for a certain scope there is freedom of choice to define some terms as basic and other terms as empirical. Particularly it’s true for interphase interaction. The choice of equations form may influence the nature of solution. With all this going on the equations form changes with changes of the flow regime. And in order to take
into consideration all regimes of the flow and correction factors one needs a good deal of empiric information. The only criteria is utility for that very purpose which for all the analysis is carried out. All the alternatives need experimental check. Simple equations are unlikely possible and concern with only much idealized models which are geometrically simple and at best work as approximation for far more complicated real-world example.

The flow in the chamber of the phase separator is conditionally divided into diphasic core and turbulent layer which is $\delta$ thick. Friction in the interface is the source of resistance head of the flow.

The interface developed in the swirled flow on the curvilinear surface has a row of peculiarities in comparison with the flat flow. As the result of having longitudinal curve centrifugal forces spring up and hence the pressure gradient does in thickness of the interface. The picture of the flow in this case is similar in many aspects with the flow between rotating cylinders. In this case velocity distribution $U$ is realized according to the law $UR = \text{const}$ (the law of free swirl).

The system of differential equations of the spatial interface in incompressible liquid on the curvilinear wall generally in the presence of longitudinal and transversal gradients of pressure gives the momentum equation in projections on cylindrical coordinates:

$$\frac{\partial \delta_{uR}}{\partial R} = \frac{\tau_{uu}}{\rho U^2}, \quad \frac{\partial \delta_{\alpha \alpha}}{\partial R} + \frac{1}{R} \left( \delta_{\alpha \alpha} + \delta_{\alpha \alpha} + \delta_{\alpha \alpha} - \delta \right) = -\frac{\tau_{uR}}{\rho U^2},$$  \hspace{1cm} (1)

where $R$ is radius of curvature, $\tau$ is friction tension, $\rho$ is density, $\delta_{uR}$ is momentum thickness of radial flow, $\delta_{\alpha \alpha}$ is momentum thickness of circumferential flow, $\delta_{\alpha \alpha}$ is momentum thickness of circumferential flow in the radial direction; $\delta$ is displacement thickness, $\delta$ is interface thickness.

The system (1) gave the system of quasilinear differential equations for partial derivatives of first order with two unknown quantities: $\delta_{uR}$ and $\varepsilon = \tan \theta_0$, where $\theta_0$ is taper angle of ground current line.

The results of tests for visualization of ground current lines show that the taper angle of ground current line never depends on the radius and is practically equal to design value

$$\theta_0 \approx 59.4^\circ \left( \tan \theta_0 = \varepsilon = 1.689 \right).$$

Methods from theory of systems of quasilinear differential equations made it possible to carry out integration of equations for the case of circular current lines and of rotation according to the law of free swirl ($C = UR$). It gave the expression of momentum thickness in circumferential and core directions:

$$\delta_{uR} = 0.0786 \left( \frac{V}{U} \right)^{0.2}, \quad \delta_{\alpha \alpha} = 0.036 \left( \frac{V}{V_2} \right)^{0.2} L_{k}^{0.8}$$  \hspace{1cm} (2)

where $v$ is kinematic density of the liquid, $V_2$ is axial velocity, $L_k$ is current length of the chamber.

These expressions make it possible to evaluate momentum thickness and therefore friction tension on the cylindrical wall of the tube.
Researching hydrodynamics of swirled flows from the point of view of mechanics of heterogenic mediums is a great problem that concerns first of all with the difficulties of solution of the ultimate task to define velocity and pressure fields. Such a problem can be solved only provided there are simplifications in balance equations of mass and momentum in the flows.

The course of transmitting air-enriched water through the phase separator gave separation gas-liquid mixture that could be rendered as a well-marked border of the phases. That’s why the given mathematical model considers performance of two different phases.

The radial movement of the liquid in the rotating flow is ridden by centrifugal force, resistance force and also by some influence caused by incidental interaction of the particles and the flow.

The free surface of the phases is the surface of equal pressure. This surface is defined by character of pressure distribution in the liquid ring round radius and along the length and also by pressure distribution of in the gas vortex. As a rule the pressure change is ignored with minor velocity. The pressure is considered to be constant in this case. The border of phases separation gets fixed at the radius when pressure of the gas vortex and the liquid ring are equal.

To design a mathematical model of the swirled flow in the chamber of the phase separator the differential equations system of the movement of viscous incompressible liquid is taken as the original one.

The border of phases gets fixed at the radius when static pressure of the gas vortex and the liquid ring are equal.

The task to integrate equations of the movement of the swirled diphasic flow is considered in the presence of obligatory initial conditions: those of static pressure at the radius $R_k$; of total pressure at the radius $R_k$; of static pressure of gas in zero section. The radius of the chamber $R_k$ should be established, mass gas consumption considered to be established and constant.

Generally the task of phases interaction in the swirled flow is characterized by seven equations

The block of equations to characterize the movement of the gas vortex consists of three equations:

- state equation
- energy equation of the gas flow (only axial velocity is taken into consideration)
- continuity equation for the gas flow

These equations define pressure, density and velocity in any section of the gas flow if the accepted constants of the total pressure, its mass consumption and the square of gas flow are known.

The formal parameter by means of which the liquid ring influences the course of the gas flow is the square of the open flow area of the gas vortex $F_{gas}$ in the equation of the gas balance:

$$\frac{F_{gas}}{F_k} = \frac{P^{\text{dyn}}_k}{P^{\text{total}}_k - P^{st}_{gas}}$$

where $F_k$ ($F_l$) is the square of the liquid ring, $P^{\text{dyn}}_k$ is the liquid dynamic pressure in the circumferential areas of the chamber, $P^{\text{total}}_k$ is the total pressure of the liquid, $P^{st}_{gas}$ is the static pressure of the gas vortex.
What is evident from the analysis of the form (3) is that the higher the dynamic pressure in
the circumferential area of the chamber is and the higher the static pressure in the gas vortex,
the more the square of open flow the area of the gas vortex $F_{gas}$ is.

The liquid performance is characterized by the following equations:

- energy equation
- continuity equation for the liquid ring
- Bernoulli differential equation (takes account of the axial constituent of the flow
  velocity in the liquid ring)

The system of these seven equations is closed and defines parameters of the gas-liquid
flow in any section if the dynamic pressure of the liquid in the circumferential direction is
known.

In order to turn from the section being considered to the nest section when doing
integration, it is necessary to define changes of the dynamic pressure at the step Obviously it
will decrease as the swirled flow under the influence of the viscosity will start losing its spin.

The dynamic pressure loss is explained by friction in the interface. The main characteristic
of the interface is momentum thickness that depends upon the total velocity. It is necessary
for the complicated three-dimensional flow to define the total momentum thickness $\delta_x^{zz}$,
provided the sum of quantities for circumferential and consumed movements is equal to the
quantity of the summarized movement. Having defined the value of $\delta_x^{zz}$ with its components
according to the equations (2):

$$
\delta_x^{zz} = \delta_x^{zz} \frac{U^2}{V_x^2 + U^2} + \delta_x^{zz} \frac{V_x^2}{V_x^2 + U^2}
$$

one gets tensions in the form of [3]:

$$
\tau_a = 0.01256 \left( \frac{U \delta_x^{zz}}{V} \right)^{-0.25} \cdot \rho U^2, \quad \tau_c = 0.01256 \left( \frac{V \delta_x^{zz}}{V} \right)^{-0.25} \cdot \rho V^2,
$$

where $\tau_a$ is friction tension on the wall in the circumferential direction, $\tau_c$ is in the axial
direction.

Then the pressure loss is:

$$
\Delta P_{dyn} = \frac{(U \tau_a + U \tau_c)2 \pi \rho \Delta R_x}{\rho_{\text{liq}}}
$$

Theoretically integration of parameters of the gas vortex can be derived to the endless
length, provided its pressure can go down to zero endlessly and the velocity can increase
endlessly. In fact the length of the chamber is limited and the hydraulic route behind the
chamber of the phase separator doesn’t allow pressure to go lower than the defined value that
provides the established gas consumption. Generally in doing calculations for parameters of
the flow in the chamber of the definite length $L_k$ with established initial parameters in the
zero section the demanded pressure may be attained along the length which is less than the
length of the chamber. That means that theoretically the gas vortex squeezed by the liquid
ring must get destroyed. If this length approaches to zero, then the phase separating flow can’t
exist even in the zero section [4].
Pilot researches are the main test of the theory validity that allows applying the results of theoretical designs for practical purposes. In order to run pilot researches there was produced a pneudraulic test bench with multi-channel method of recording and processing measuring results on the basis of HS A/D transformer that makes it possible to run researches for hydrodynamics of the swirled flow in the chamber of the passive phase separator.

The test bench provides supply of the operating liquid (water) with various consumption (up to 0.65 kg/sec) and of the gas (air) with consumption up to 1.578·10⁻³ kg/sec. The consumption of the operating liquid was controlled by the turbine flow sensor, the gas consumption was controlled by the rotameter. The water and the gas came through tubing to the mixer where the diphasic flow sprang up.

Pilot researches were divided into two stages. At the first stage we used the swirling chamber to measure the energetic parameters of the swirled liquid flow. This step was necessary for test a most important parameter of the algorithm, that determines the circumferential dynamic component of hydraulic head along the length of the swirling chamber under the influence of the viscosity in the boundary layer on the wall.

Then to visualize the diphasic flow and define main dependences between geometric and regime parameters the phase separator was used.

The research of the phase-separated gas-liquid flow was carried out in a special device that immediately visualizes the flow and measures main parameters at the inlet and the outlet.

The chamber of the phase separator was presented by a transparent tube with the internal diameter of 44 mm and the wall thickness of 13 mm. In the reservoir there was a tangential inlet of 8 mm to provide supply and spin of the operating body.

**Table 1.** The results of measuring total and static pressure of the liquid and the gas at the inlet and outlet of the plant with different consumptions of liquid and gas.

| Consumption kg/sec | \( P_{\text{liq in}}^\sigma \cdot 10^5 \), Pa | \( P_{\text{gas in}}^\sigma \cdot 10^5 \), Pa | \( P_{\text{gas out}}^\sigma \cdot 10^5 \), Pa | \( P_{\text{liq in}}^\sigma \cdot 10^5 \), Pa | \( D_{\text{gas}}, \text{ m} \) | \( L_2, \text{ m} \) |
|-------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------|------------------|
| \( \dot{m}_{\text{gas}} = 0.51 \cdot 10^3 \text{ kg/sec} \) | 2.08                            | 1.94                            | 2.02                            | 1.05                            | 0.044 + 0.028    | –                |
| \( \dot{m}_{\text{gas}} = 1.311 \cdot 10^3 \text{ kg/sec} \) | 1.92                            | 1.80                            | 1.92                            | 1.02                            | 0.044 + 0.022    | –                |
| \( \dot{m}_{\text{gas}} = 6.939 \cdot 10^4 \text{ kg/sec} \) | 1.67                            | 1.60                            | 1.49                            | 0.81                            | 0.042 + 0.018    | –                |
| \( \dot{m}_{\text{liq}} = 0.2815 \text{ kg/sec} \) | 0.96                            | 0.95                            | 0.97                            | 0.71                            | –                | 0.54             |
| \( \dot{m}_{\text{liq}} = 0.2153 \text{ kg/sec} \) | 0.61                            | 0.62                            | 0.67                            | 0.48                            | –                | 0.394            |
| \( \dot{m}_{\text{liq}} = 0.0978 \text{ kg/sec} \) | 0.25                            | 0.13                            | 0.19                            | 0.13                            | –                | 0.134            |

\( P_{\text{liq in}}^\sigma \) is statistic pressure of the liquid at the inlet, \( P_{\text{gas in}}^\sigma \) is statistic pressure of the gas at the inlet, \( P_{\text{gas out}}^\sigma \) is statistic pressure of the gas at the outlet, \( P_{\text{liq in}}^\sigma \) statistic pressure of the liquid at the outlet, \( D_{\text{gas}} \) is the diameter changes of the gas vortex by the length of the chamber, \( L_2 \) is the length of stable being of the gas vortex.

To research the character of the changes of the gas vortex diameter along the length of the chamber the consumption of gas was changed in the range of 3.45·10⁻⁴…1.58·10⁻³ kg/sec with
the constant consumption of the liquid which is equal to $m_l = 0.51 \text{ kg/sec}$. For each gas consumption one measured total and static liquid pressure in the circumferential area (on the wall) in the initial section of the phase separation (see Table 1) and also photographed to measure the diameter of the gas vortex (Fig. 2).

Then to define the dependence of length of the gas vortex (or length of the diphasic swirled flow being) on consumption of liquid with the constant gas consumption $m_g = 3.44 \times 10^{-4} \text{ kg/sec}$ one changes liquid consumption in the range of $0.098…0.282 \text{ kg/sec}$. With the help of photos the length of the gas vortex was defined (Fig. 3).

The analysis of calculation and experimental data showed that accuracy of calculation algorithm is satisfactory and is not higher than 5% in comparison with experimental results.

The results of calculations and experiments gave dependence (Fig. 4) of the gas vortex length (or the length of the diphasic swirled flow being) on the liquid consumption that physically corresponds to the circumferential velocity of liquid in the initial section.

![Figure 2. The swirled diphasic flow with gas consumption $m_{gas} = 3.45 \times 10^{-4} \text{ kg/sec}$]. Changes of the gas vortex length $0.042…0.016 \text{ m}$

The gas content in the flow constitutes 0.07 %.

Pilot and calculation researches show:

- the gas vortex length in the diphasic flow with the constant gas content decreases along the length of the tube as the result of liquid spin decrease caused by breaking effect of the wall;
- the length of the swirled diphasic flow being in the round tube definitely depends on the flow spin in the initial section, the spin decrease leads to decrease of the length;
- consumption decrease leads to the fall of axial velocity and axial velocity of liquid remains almost unchanged;
- changes of gas static pressure happen only in the initial area, and then remains constant along the length of the chamber.

![Figure 3. The length of the stable gas vortex $l_{gas.v.} = 0.394 \text{ m}$]. Liquid consumption $m_{liq} = 0.215 \text{ kg/sec}$. The gas content constitutes 0.16 %
The designed methods allow to evaluate interdependence of the basic parameters of the swirled monophasic and diphasic flows with tangential supply of liquid and gas-liquid mixture and to define influence of geometry of the chamber flowing part on the basic parameters of the flow.

It is significant that the offered algorithm of calculation for the flow in the chamber of the phase separator takes into account changes of liquid characteristics along the length of the chamber caused by temperature changes of the operating liquid.

The developed model lets not only calculate the nominal regime of the phase separator functioning but also helps foresee possible breakdowns and in advance take measures to eliminate the revealed defects in the process of its designing.

Figure 4. The dependence of the gas vortex length on liquid consumption

Further research of flow regularities for heat exchange and mass transfer of swirled flows in axial-symmetric channels, systematization of these data and designing universal calculation methods for such flows are topical scientific and practical problem. This research results will be widely applied for purposes of various engineering fields.

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