Managing the processes accompanying fluid motion inside oil field converging-diverging pipes

M Ya Khabibullin

Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russian Federation

E-mail: m-hab@mail.ru

Abstract. In recent years, there is an increased interest in pipes with regularly variable section area (converging-diverging pipes) in the oil chemical industry. At the same time, there is no simple engineering technique for calculation of hydrodynamic characteristics of such devices, which significantly impedes computations for mass exchange processes inside them. Attempts to concentrate energy dissipation and their control near the phase boundary were mainly directed at using the fluid flow pulses induced by an external generator, alternating displacement field, pulses caused by fluid flow through the conduit with a variable cross-section. As a result, it has been revealed that the forces determined by action of convective acceleration are capable of causing a significant deformation and breakage of disperse inclusions (drops and bubbles). For rigid particles, the action of the convective acceleration leads to a periodic impulse renewal of liquid near the surface of the rigid particle.

1. Introduction

Aspiring to increase the efficiency of operation of oil field equipment while preserving its high reliability, researchers and developers are trying to apply the conduits with regularly changing cross-section (converging-diverging pipes) to increase the hydrocarbon liquid pumping in gathering, treatment and transportation systems used with oil and petroleum products. In 1970, for example, there was a proposal to use the periodically changing speed in such mass exchange device to accelerate dissolution of solids [1]. The work [2] described a new type of tubular-turbulent reactors intended for fast polymerization processes. The work [3] studied the regularities of turbulent mixing in tubular apparatuses of the diffuser-confuser type. A similar device is proposed for treatment of capillary-porous particles with liquids: impregnation and extraction [4]. Thus, there is an increased interest in converging-diverging pipes in the petrochemical industry in the recent years. At the same time, there is no simple engineering technique for calculation of hydrodynamic characteristics of such devices, which significantly impedes computations for mass exchange processes inside them.

2. Results and Discussion

The last 20 years saw a trend in developing one of promising directions in intensifying the inter-phase exchange in heterogeneous mediums: input of energy predominantly in close vicinity of the phase boundary [5-7]. Indeed, turbulence transition throughout the mass of continuous mediums, e.g., in agitating equipment, is an undesirable outcome related to increase in energy costs for non-productive dissipation of power. Thus, the same amount of energy supplied to a piece of equipment may be used...
with various energy efficiencies that may be defined as a ratio between the useful capacity $N_n$, spent to dissipate and displace the phases with respect to each other to the total capacity $N$, lost in the equipment. The total capacity may be represented as a sum of the capacities: $N = N_n + N_d$, where $N_d$ is the power dissipated through the volume far from the surface of the disperse phase particles: near the actuator, at the apparatus' walls, throughout the continuous medium when disintegrating turbulent vortexes, $W$.

The efficiency value influences the area of the inter-phase surface, the speed of relative movement of the phases, and in the end, the speed of the mass-exchange processes. In its own turn, the efficiency depends on the design of the equipment, its standard parameters, mainly, on the method used to input the energy, that is, on the nature of working medium displacement (rotary, translational, swirling, oscillating, etc.).

The work [6] provides data on influence of specific energy dissipation speed $\varepsilon$ onto drop size in emulsification: the maximum drop diameter $d_{\text{max}}$ for mechanical actuators at $\varepsilon \sim 10^3…10^4$ W/kg is 50-100 µm, for pulse energy input and the same values of $\varepsilon$, the diameter $d_{\text{max}} \approx 2…8$ µm, that is, impulse application provide drops of about an order of magnitude less.

Attempts to concentrate energy dissipation near the phase boundary were mainly directed to using the fluid flow pulses induced by an external generator, alternating displacement field, pulses caused by fluid flow through the conduit with a variable cross-section.

This paper is dedicated to studying the third case: flow of uniform incompressible fluid through a pipe consisting of confuser-diffuser elements similar to a Venturi tube (Figure 1).

As a result of the research, a distribution of local speeds, pressure values, turbulence kinetic energy and energy dissipation rate was obtained for a pipe with periodically variable cross-section, basing on a $(k-\varepsilon)$ model of turbulence [8] with a Finite Element Method.

Figure 2 shows a fragment of speed field at the interface between confuser and collar.

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**Figure 1.** Diagram of confuser-diffuser pipe element with periodic profile.

**Figure 2.** Calculated speed field near the interface between confuser and collar for a flow of $7.8 \cdot 10^{-4}$ m$^3$/s (length of arrows is proportional to the local speed, the maximum speed is 10.4 m/s).
However, in the engineering practice, using a one-dimensional model of liquid flow in Venturi tubes is quite possible [9].

At some arbitrary cross-section $x$, diameter of the confuser is determined by the expression
\[ D_x(x) = D - B_x, \]
where $B = (D - d)/L_1 = 2\tan(\alpha/2)$; $D$, $d$, $L_1$, $\alpha$ are dimensions (see Figure 1).

The area of this cross-section is determined with the formula
\[ S_k(x) = (\pi/4) (D - B_x)^2, \]
and mean flow of liquid through it is determined with the formula
\[ w_k(x) = Q / S_k(x), \]
where $Q$ is a volume flow rate of the liquid, $m^3/s$.

Similarly, for a diffuser with a shifted coordinate system ($\xi = x - L_1 - L_2$) it is not complicated to obtain an expression to calculate the diameter of its cross-section
\[ D_\xi(\xi) = d + A\zeta, \]
where $A = (D - d)/L_3 = 2\tan(\beta/2)$; $L_3$, $\beta$ are dimensions, (see Figure 1);

for the area of this section
\[ S_\xi(\xi) = (\pi/4) (d + A\zeta)^2, \]
as well as the mean liquid flow through it
\[ w_\xi(\xi) = Q / S_\xi(\xi). \]

In a general case, acceleration $a$ of the liquid flow moving along the $x$ axis with a speed of $w$ is a sum of the local (the first summand) and convective (the second summand) components: $a = dW/dt = \partial w / \partial t + w(\partial w / \partial x)$, where $t$ is time in seconds.

In the case of stationary flow that we are considering, the local acceleration $\partial w/\partial t$ is equal to zero. However, a particle of liquid or gas being displaced with the flow is subjected to a convective acceleration that may be expressed in the following form
\[ a = \frac{\partial}{\partial x} \left( \frac{w^2}{2} \right). \]

The forces determined by action of convective acceleration are capable to cause a significant deformation and breakage of disperse inclusions (drops and bubbles). For rigid particles, the action of the convective acceleration leads to a periodic impulse renewal of liquid near the surface of the rigid particle [9].

Let us find out the distribution of the convective acceleration on confuser and diffuser. Taking into account the expressions (2), (3), (7) and transforming the expression for the confuser, we get
\[ A_\xi(\xi) = 32B(Q/\pi)^2(D - A\xi)^5. \]

Similarly, for the diffuser, from the formulas (5) - (7) it follows that
\[ A_\xi(\xi) = -32A(Q/\pi)^2(D + A\zeta)^5. \]

The $\leftarrow$ «» sign in the expression (9) is an evidence of flow recompression accompanying its expansion; the $\leftarrow$ «+» sign in the expression (8) is an evidence of flow acceleration accompanying its constriction.

The next important characteristic of a flow inside a pipe with periodically varying cross-section is a frequency of pressure and speed pulses arising due to its expansion and compression [10].

3. Experimental part

Let us consider a diffuser part of a Venturi tube. Let us find the time required of a liquid particle having started in a point $\xi = 0$ to reach an arbitrary selected cross-section $X$. According to Euler [8], the flow rate is determined by an expression $w = dx/dt$, with the implication that $dt = dx / w$. Integrating this expression from 0 to $X$ with respect to the spatial coordinate and from 0 to $t_x$, with respect to time and taking the ratios (5), (6) into consideration, we obtain
\[ t_x = \int_0^X (\pi/4) (d + A\zeta)^2 d\xi = (\pi/12QA)[(d + A\zeta)^3 - d^3]. \]

Having substituted $X = L_3$ into the expression (10), we get the total time required of the liquid particle to pass through the length of the diffuser
\[ t_{L_3} = (\pi / 12QA)(L_3^3 - d^3) = (\pi L_3/12Q)(D^2 + Dd + d^2). \]

It is plain to see that in the right part of the last-mentioned equation we have the ratio between the
volume of a truncated cone formed by the diffuser and the liquid flow, that is,

\[ t_{L3} = \frac{W_d}{Q}. \quad (12) \]

where \( W_d = (\pi L/12) (D^2 + Dd + d^2) \) is the volume of liquid in the diffuser, \( m^3 \).

Similarly, we may get the total time required of a liquid particle to cover the length of the confuser

\[ t_{L1} = \frac{\pi L_1/12Q)(D^2 + Dd + d^2)}{W_k/Q}. \quad (13) \]

where \( W_k = (\pi L_1/12)(D^2 + Dd + d^2) \) is the volume of liquid in the confuser, \( m^3 \); \( t_{L1} \) is the time that the liquid particle spends to pass through the constricted (diameter \( d \)) cylindrical segment of the collar, \( t_{L2} = \pi d^2L_2/4Q \), \( s; t_{L4} \) is the time that the liquid particle spends to pass through the wide segment of the collar (diameter \( D \)), \( t_{L4} = \pi D^2L_4/4Q \), \( s. \)

The total time required of the liquid particle to pass through a single Venturi tube element with a length of \( L = L_1 + L_2 + L_3 + L_4 \) comprises

\[ Z = t_{L1} + t_{L2} + t_{L3} + t_{L4} = \Sigma W / Q. \quad (14) \]

and it is nothing other than the pressure, speed and acceleration oscillation cycle for a liquid particle that is moving together with the flow (\( \Sigma W \) is the total volume of liquid in a single Ventury tube element of length \( L \)).

4. Conclusions

A simplified engineering computation technique allows determining the distribution of speed, acceleration and pressure values along the pipe with a regularly varied cross-section with a satisfactory accuracy, as well as the oscillation frequency.

Hydraulic resistance and total loss of energy in the converging-diverging pipe under consideration is somewhat lower than in a straight cylindrical pipe of the same length and a diameter equal to the diameter of the lesser collar, all other things equal.

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