Analysis of Causes of Non-Uniform Flow Distribution in Manifold Systems with Variable Flow Rate along Length

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Abstract. The uniformity of flow distribution in perforated manifolds is a relevant task. The efficiency of water supply, sewerage and perflation systems is determined by hydraulics of the flow with a variable mass. The extensive study of versatile available information showed that achieving a uniform flow distribution through all of the outlets is almost impossible. The analysis of the studies conducted by other authors and our numerical experiments performed with the help of the software package ANSYS 16.1 were made in this work. The results allowed us to formulate the main causes of non-uniform flow distribution. We decided to suggest a hypothesis to explain the static pressure rise problem at the end of a perforated manifold.

1. Introduction

Flows with variable mass widely are spread in the water supply, ventilation, sewage systems (branching conduits, slotted pipe, distribution channels, etc.). They can be used to transporting and to supply to the water treatment station and to sewage treatment station, water distribution in supply and dividing systems of water pumping station, can be an integral part of most sedimentation facilities (distribution channel of gravity tank, drain system filters and contact clarifiers), ventilation systems, etc.

Despite the widespread use of flow with a variable mass in the apparatus for different purposes and a large number of studies in this area, the practical problem of uniform distribution has not been resolved to this time.

In this paper a detailed analysis to identify causes of non-uniformity flow rate on the basis on analytical review of earlier studies and comparison those with the studies made by the authors of this work will be presented.

2. Analytical and empirical analysis of fluid with variable flow

Hydraulics of flow with a variable mass divides the perforated manifolds on both long and short [1]. Long manifolds distribute the water in the systems of transportation of water settlements and their calculation according to the existing methods in our view adequately describes the situation [1]. Short manifolds are manifolds of apparatus for various purposes. In this case the uniformity of the mass distribution determines the longevity and efficiency of design. Because the work poses the problem of providing uniform distribution of water or air flow, then a priori the object of research are short
manifolds with variable flow along the length. Calculation of flows with a variable mass in domestic practice is based on theoretical studies by G. A. Petrov [2].

\[
\frac{d (Mv)}{dt} = F + \frac{dM_1}{dt} \theta_1 - \frac{dM_2}{dt} \theta_2
\]

\[
\frac{\alpha_\theta}{g} \left( v \frac{\partial^2 v}{\partial x^2} + \frac{\partial v}{\partial t} \right) + \frac{d}{dx} \left( \frac{p}{\gamma} \right) + \frac{v}{g} \left( \frac{\partial \alpha_\theta}{\partial x} v + \frac{\partial v}{\partial t} \right) + \frac{\alpha_\theta (v - \theta)}{gQ} \left( \frac{\partial Q_i}{\partial v} + \frac{\partial Q_i}{\partial t} \right) + \frac{\alpha_\theta (\theta_2 - v)}{gQ} \left( \frac{\partial Q_i}{\partial v} + \frac{\partial Q_i}{\partial t} \right) = 0
\]

where \( M \) is the mass flow; \( F \) is the projection of resultant force in direction of motion; \( v \) is a projection velocity of movement in the primary flow direction, \( \theta_1 \) and \( \theta_2 \) projection velocity, attachable and detachable particles on the direction of the main flow; \( t \) – time, \( \gamma \) – specific weight of liquid, \( A_\theta \), the \( A_B \)-coefficients taking into account respectively the non-uniformity distribution of velocity and kinetic energy for the living section of the main flow, detachable or attachable; \( p \) – piezometric head; \( Q \) – flow rate, which can be represented for the i-th cross-section area of \( \omega_i \) via the integral equation.

\[
Q = \omega_i v_i
\]

For steady motion the equation (2) after integration will take the form:

\[
z + \frac{p}{\gamma} + a_\theta \frac{v^2}{2g} + h_i + \frac{1}{g} \left( \frac{\alpha_\theta v - \alpha_p v}{\omega} \right) dQ = \text{const}
\]

where \( h_i \) – pressure losses along the length.

With continuous distribution of the detachable flow relationship (4) gives the lowering of the piezometric pressure, which reaches a minimum at a certain length \( l \), then the value of \( R \) increases.

Equation (4) is written under the assumptions that materially affect the calculation results. In this case, the analysis excluded the inertial forces associated with the curvature of streamlines in the separation or connection of the water masses. The energy equation applies only for the velocity parallel to the direction of movement of the main flow, although from the Navier-Stokes equations written in the form of Gromeka it is known that the differential of the total energy is included in the equation of impulses in a projection to all coordinates. At a next step (the case of detach of flow in a perforated manifold) Petrov G. A. took into account the pressure loss caused by the different devices (unit tee) and head loss at an abrupt change of direction of the flow (separating mass). It was noted head losses in the device tee with some exaggeration is related to the velocities in the cross-section directly after the separation of the flow.

Head loss at the change of direction of flow QB related (approximately) with velocities in the pipe branches. These losses per unit weight of fluid expressed in the following way:

\[
h_{\text{noy}} = \frac{\xi}{2g} v^2 \gamma Q
\]

Numerous studies of flow distribution in perforated manifolds was sent at finding the optimal ratio of parameter, which, according to the researchers, could smooth the non-uniformity of flows through perforated holes (branch).

Photo of a current in the perforated manifold with flow separation by branches according to Jafar M. Hassan’s and others is shown in figure. 1 [3]. The pictures clearly shows that discharge through the last outlet in branches 4 and 5 occur over the entire area of the cross section, while the first two branches have a relatively low discharge (14% and 17% of the total flow rate supplied to the perforated manifold) [3].
The formation basis of calculated dependencies for flow with variable mass has become several theoretical and practical assumptions:

1. At the end of the distribution manifold is formed a zone of high statistical (piezometric) pressure due to the so-called "deceleration of flow" due to the transition of kinetic energy into potential. This effect is noted by almost all researchers studying movement in pressure conduit.

2. Rise static pressure causes increase of discharge from the last outlet. Calculation of pressure and velocity is realized on the basis of the equation D. Bernoulli [4-11].

3. Uniform distribution from the outlets located along the axis of the perforated manifold it is possible if the head losses $\sum h$ in the distribution manifold is equal to the restoring pressure $Prec$ about the last branch, $\sum h = Prec$. In this case there should be no pressure increase and thus cause non-uniformity distribution [10,12]. This idea was implemented in the simulation of unconfined channels of the irrigation system to Syntagma Salihu Abubakar [9], which received almost equal costs in the holes, and Ramirez-Guzman and Manges for similar tasks [8]. The latter researchers have found a discrepancy in the costs of the holes is not more than 6.5%. Good results for gravity flows are not random. The authors got in their research the uniformity of flow distribution by manipulating the slope of pipelines and thus were compensated pressure losses and braking of the flow.

4. Water flow rate in the branches depends on the velocity distribution in the manifold (dispenser) and the magnitude pressure recovery $Prec$. These conclusions appeared in the works published after 1979. The difference in the values of flow coefficient for different ports depending on their distance from the entrance and the velocity of the dispenser clearly marked in later researches. Moreover the horizontal velocity in the perforated manifold determines the compression degree of the flow in the branch.

5. In domestic research the basis of theoretical analysis is the equations of G. A. Petrov. However the proposed calculation methods based on experimental dependencies for flow compression coefficient at the entrance to the branch or the opening, $\varepsilon$, the resistance coefficient $\zeta$, the degree of non-uniformity distribution of flow in branches, $\beta_q$, and determine the pressure near the branches [1].

In this researches, we have left outside of the analysis of the situation relating to the decision of private tasks, such as optimal ratio of the dispenser area to the area of the openings [5,10], the equality of the diameter of the manifold and branches diameters [14], although for the formation of our conclusions of those researches have been useful.

By studying the above researches we noticed that to determine the pressure about each orifice or branch, the authors use the Bernoulli's equation based on the pressure at the end of the manifold. The pressure was calculated by empirical formulas or was determined experimentally. The corresponding dynamic pressure was taken away from the pressure at the end of the dispenser and was received a piezometric head around the previous orifice.

The pattern of expiry of the orifices of the perforated gravity-flow channel is shown in Figure 2. The study was done in the laboratory of hydraulics of the University [14]. The model was represented by a short perforated channel with zero slope with length 0.6 m. In the middle of the channel was a lowering of the water level, then at the end of the channel level increased.
Figure 2. Free falling jet through the orifices of the perforated channel.

The level rise and, consequently, the pressure rise near the last branches was the result of the fact the conveyance capacity of the perforation orifices was not sufficient to pass the flow of a perforated channel. This circumstance led to the fact the flow has hit the vertical wall at the end of the manifold and has created a circulation zone with a horizontal axis and reversed backward relative to the main stream currents. The increase in pressure over the apertures of the second half of channel has led to the increase in conveyance capacity of these apertures.

From experience, represented in Figure 2, it follows the stream characterized by complex structure, which violated the conditions parallel the jets of stream and, consequently, the application of Bernoulli's equation to describe the process can be used only conditionally.

The diagrams of currents Figure 3 show the effect of compression of the stream at the beginning of branch for $V_0 = 2.5$ m/s more significant than for $V_0 = 0.55$ m/s.

![Figure 3](image)

Figure 3. a) the Distribution of pressures and velocities, the input velocity manifold $V_0 = 0.55$ m/s. b) the Distribution of pressure and velocity, the input velocity manifold $V_0 = 2.5$ m/s.

Experimental studies were accomplished at velocity of input $V_0$ from 0.55 m/s to 5.0 m/s. The aim of the experiment was the comparison of the experimental values of pressure recovery $P_{rec}$ and the head losses $h_{hf}$ with their assessment according to the Bernoulli equation.

According to the Bernoulli equation in the distribution manifold on its axis
Equation (6) means that sum of the difference in static pressure in the last section of the dispenser and in the initial section (the increase in pressure \( P_c \) (Figure 3) with the pressure loss must be offset by a drop in dynamic pressure at the beginning of the manifold.

To definition the pressure loss flow coefficient \( \mu \) was made according to the research of Ibrahim TAS and Raymond A. Brian (1986), \( \mu = 0.56 \), the compression ratio according to the results of the numerical experiment \( \varepsilon = 0.75 \); conformably, the speed ratio is \( \phi = \mu / \varepsilon = 0.75 \) [15]. Then the resistance coefficient for the latest openings \( \zeta = 1 / \phi^2 - 1 = 0.78 \). The energy loss along the length of the perforated manifold was negligible because of its short length.

In Figure 4 dependences \( P_c \) and the dynamic pressure from the velocity in the inlet section of the manifold. The dependencies presented in dimensional form for clarity.

The data in Figure 4 is indicating that the magnitude of \( P_c \) essentially exceeds the dynamic pressure. Hence the reason for deceleration of flow is not only the velocity decrease through the selection of water branch and orifices. Our hypothesis is that the increase of the pressure is provoked by insufficient bandwidth of the orifices and branches.

![Figure 4. Diagram dependencies \( P_c \) from \( V_0 \) and \( \gamma \times V_0^2 / 2g \) from \( V_0 \).](image)

**3. Conclusion**

The analysis of theoretical and experimental research allowed to formulate proposition the implementation of which will ensure maximum approximation to the uniformity distribution of flow with a variable mass:

1. Supply and distribution systems of water or air flow perforated manifold is self-consistent. Conveyance capacity of ports (branches) should correspond to the pressure and flow rate in the manifold or distribution channel. In this case the value \( P_{rec} \) will be minimal.

2. Velocity in perforated manifold has to be constant. This condition shall ensure the equality of compression and flowage coefficients. For the first time this conclusion is confirmed experimentally by Van Der Hegge Zijner, who has used the manifold with variable cross-section [6]. The practicability of a conical manifold was confirmed also by the numerical experiments Jafar М. Hassan and others applied program CFD FLUENT [3].

At the same time interpretation of item 1 and item 2 can't be single-valued. Obtained experimentally some circumstances should be taking into account in the projecting and investigation of flows systems with variable mass. These circumstances are explained below.

3. Fluid port and the continuous port have smaller resistance in comparison with branches [16]. The continuous port provides the best uniformity of flow distribution.

4. Almost perfect uniformity distribution of flow in a perforated manifold is provided when the ratio of the total area of ports to the area of the manifold is less than 0.075 [13]. Keller J.D. this
condition exposes more gently. The ratio of areas should be less than unity. This result means the drainage properties of high resistance is useful in our problem. However, we should not forget that the reduction in ports square will lead to an inevitable increase in pressure in the initial sections of the system.

5. To minimize energy losses associated with resistance along the length and local resistances, to reduce the compression coefficient, the velocity in the perforated manifold should be less than unity, of the order of 0.5-0.6 m/s. Velocity in ports should be more of the order of 1-2 m/s.

Thus, despite the large amount of conducted research the results of which are sometimes inconsistent the problem cannot be considered fully resolved.

Checking proposition (hypothesis) No.1 is the main objective of our further research.

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