

THEORETICAL AND EXPERIMENTAL INVESTIGATION OF HYDRAULIC JUMPS IN CLOSED CONDUITS

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This article examines the conditions for the development of hydraulic jumps in pipelines, the types of jumps, and the locations where they typically occur. A theoretical method for determining the relationship between conjugate depths is presented, along with its influence on the hydraulic regime of pipeline operation. In gravity pipelines, free-surface, pressurized, and mixed flow regimes may appear. The transition from pressurized to free-surface flow is smooth, whereas the reverse transition involves a surface discontinuity similar to a hydraulic jump in open channels. For a given discharge, the jump location depends solely on flow rate; as the flow increases, the jump shifts upstream. The behavior of hydraulic jumps and resulting flow choking in circular pipes remains insufficiently studied, though theory and experiments show encouraging agreement. This analysis is important for multipurpose water conduits, where free-flow sections are preferable for energy applications.

Keywords: *pipeline, mixed regime, conjugate depth, air pocket, flow*

Introduction

A hydraulic jump is a sudden transition from a supercritical to subcritical flow, with discontinuity in flow depth as well as in pressure and velocity field at the transition point [1]. The transition is sudden and most jumps involve a vigorously tumbling flow region, called roller, where much kinetic energy is being lost [2, 3] (fig. 1).

- 1 and sloping sections represents an,
- 2 undesired situation for pipeline engineers which may have a bad,
- 3 influence on flow assurance as well as pipeline integrity.

The gravitational water conduit belongs to the class of long pipelines of which hydraulic calculation making values of power local losses and kinetic energy losses are negligible small compared with power losses on transportation [4, 5]. From a hydraulic point of view, concentrated air pockets in pipeline profile peaks represent an additional source of energy loss that decreases discharge in case of gravity pipelines and increases energy consumption in case of pumped pipeline systems.

In article two cases of transition of a free-flow mode of movement in pressure head in the self-flowing pipeline are discussed, a) a subtime on the bottom end of the pipeline is supported to constants, the expense changes yes its gravitational value; b) the expense remains to constants, and a subtime on the bottom end changes to its static value. For considered cases the method of definition of type and a place of emergence of a hydraulic jump is given.

Materials and Methods

A hydraulic jump is a complex two-phase open channel flow with air entrainment into water. Several numerical studies were dedicated to the analysis of air–water flow characteristics. However, few physical data are available so far due to the complexity of the measurement.

Surface deformation and air entrainment was discussed by Wang and Chanson [6]. But to date, no investigation considered the impact of flow instabilities on turbulence characterisation for strong hydraulic jumps in pipeline with substantial air entrainment and intense free-surface deformation. Kalinske and Bliss [7] first investigated different air–water flow regimes in downward sloping pipes. Pothof [8] provided a further detailed view for the previous investigation. Accordingly, air–water flow can be classified into four regimes, namely, stratified flow, blowback regime, transitional flow regime, and full air transport regime. Escarameia investigated the required water velocity to keep air pockets of a certain size stable in a downwardly inclined pipe [8, 9].

Considering the numerous parameters required to describe the turbulent two-phase flow and the complexity arising with the coupling between almost all physical processes in wide ranges of length and time scales, our knowledge on hydraulic jumps is far from a full understanding.

The air-water flow properties were investigated with an intrusive phase-detection probe. The void fraction and bubble count rate data were documented in the jump roller, together with the interfacial velocity distributions [10]. Both the turbulent fluctuation and aeration properties are basic design parameters in urban water systems in which a hydraulic jump may take place [11,12].

Lubbers and Clemens [13] investigated the size-scale effects, caused by differences in pipe diameters, on the validity of the experimental results that describe the head loss through the air pocket and the rate of gas transport in downward sloping pipes. In the last twenty-five years, significant progresses were achieved experimentally, mostly in laboratory [12, 13].

On the entire length of a pipe of gentle slope (Fig.1) the flow will be pressure one, if the flow feeding its headworks is not smaller than gravitation flow of the conduit (fig. 2)

$$Q \geq Q_g, \left(Q_g = \sqrt{H_0/S} \right), \tag{1}$$

where S is the hydraulic resistance of the pipe, Q released flow, Q_g-calculated flow.

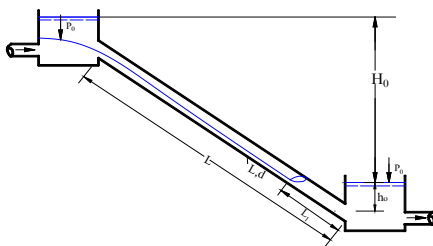


Fig. 1. Schematic diagram of the hydraulic jump

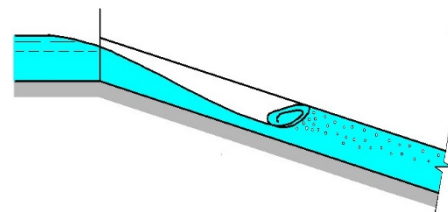


Fig. 2. Hydraulic free jump

If $Q < Q_g$ and there is a h_0 overpressure at the lower point of the pipeline, then a mixed regime of the fluid flow is developed in the pipe, at that on the $L - L_1$ length of the upper part of the pipe a non-pressure flow is developed, and on the L_1 length of the lower part a pressure flow is developed. If the pipe’s own i_0 islope is greater than critical slope corresponding the Q flow, then at the pressure flow section b_2 type curve sets up known in professional literature, therefore, at the pipe’s entrance section a critical h_{cr} depth sets up and on the surface – atmosphere pressure [14] (fig. 3). The depth along the flow direction decreasing tends to

the depth of uniform flow. Thus, at the non-pressure section flow the fluid stream is rough, and at the initial pressure section – smooth. Therefore, the fluid flow passage from non-pressure regime to pressure one, actually is a passage from rough flow to smooth one, due to which transition phenomenon is a classic hydraulic jump.

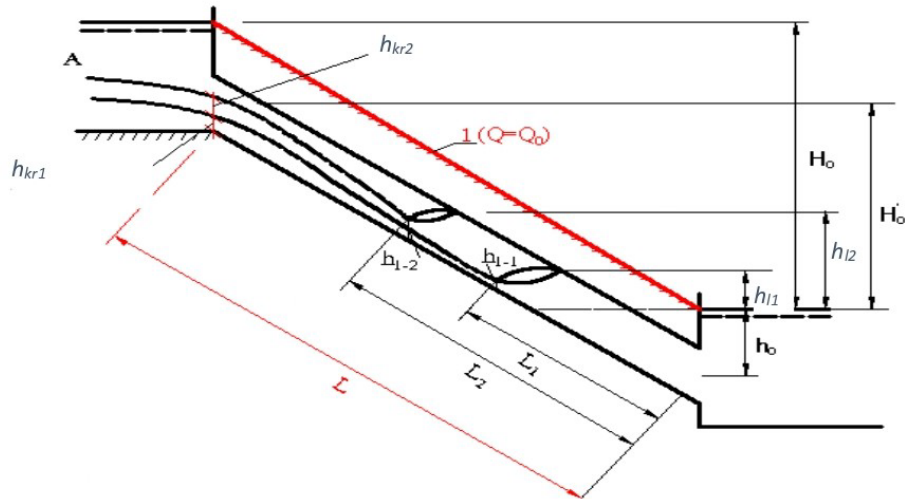


Fig. 3. Schematic diagram of the hydraulic jump

Despite researchers having studied these phenomena, air binding is still commonly found in aqueducts, since there is a lack of understanding on the movement of air bubbles and pockets in closed conduits. An experimental investigation was conducted to validate the proposed analytical method. A characteristic feature of the jump is the large amount of entrained air bubbles seen in fig. 4.

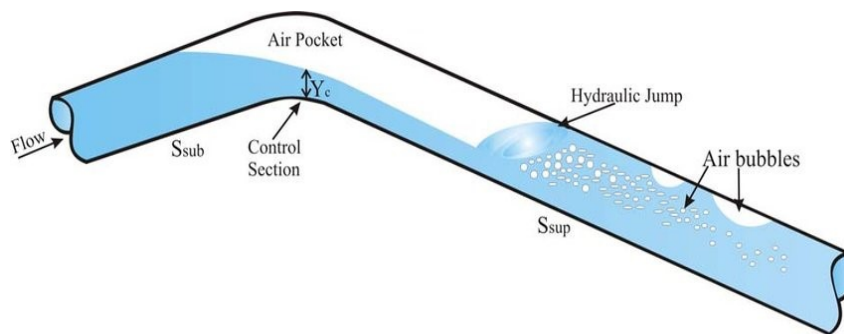


Fig. 4. Hydraulic jump in a siphon of pipes

Conjugate depths of hydraulic jump developed in open-channel flow depending on the change of the downstream reach, always are conjugate, that is the increase of one of them is accompanied by a decrease of the other one, for functions of these depths jumps are equal.

Experimental study of the above described phenomena was carried out in the hydraulic research laboratory of the institute of Water Problems and Hydro-engineering after Academician I.V. Eghiazarov, using an experimental setup made of glass pipes of 50 mm diameter (fig. 5).



Fig. 5. Experimental visualization showing air bubbles and hydraulic jump in pipeline

It is obvious that the greater of the conjugate depths of the jump developed in the closed channel is determined by the diameter of the pipe $h_2 = D/i_0$ and is independent of the $Q < Q_g$ flow intensity. On the other hand at the lower point of the pipe h_0 pipe the change of retaining pressure is accompanied by displacement of the place where the jump occurs, during which the flow remains unchanged. Thus, if h_0 increases, the jump place travels upward along the length of the pipe, therefore, the smaller of conjugate depths of the jump grows, and the larger one remains unchanged. Therefore, in the general case of a hydraulic jump developed in a closed channel we arrive at a very important conclusion – conjugate depths can also be non conjugate, that is their jump functions can be unequal. This is an important peculiarity of the closed-channel hydraulic jump.

Results and Discussion

Another peculiarity of the closed channel hydraulic jump is its occurring place relatively large displacement depending on the flow release condition $Q_g > Q = const$ retaining pressure change and retaining pressure $h_* = const$ condition flow change. Let us note that in this case the flow increase is accompanied with jump place upward travel and v.v. and the smaller of the jump conjugate depths can be changed in the range $(h_{cr} \dots h_0)$ between critical and normal depths. It is evident that in this interval there is a boundary h_0 depth which will be conjugation of the conjugated large depth $h_2 = D/i_0$. We now determine h_1 depth by equality of its and conjugate jump functions.

The function of the jump function can be written as

$$\Pi(h) = \frac{\alpha Q^2}{gA} + yA, \quad (2)$$

where A is the area of the effective cross-section, y is the distance from the gravity centre of the effective cross-section area to the free surface (fig. 6).

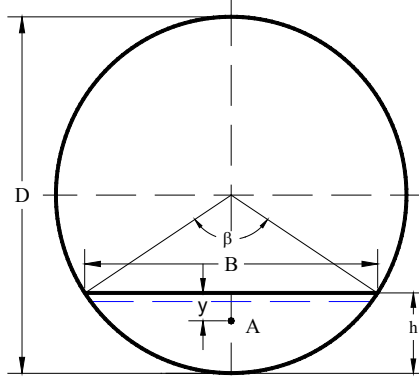


Fig. 6. Cross-section of the pipe

For the circular cross-section, we have

$$A = \frac{R^2}{2}(\beta - \sin\beta), \quad y = R \left(\frac{4}{3} \frac{\sin^3 \frac{\beta}{2}}{\beta - \sin\beta} - \cos\beta \right), \quad (R = D/2). \quad (3)$$

Jump functions will have the following views

$$\Pi(h_*) = \frac{\alpha Q^2}{g R^2 (\beta - \sin\beta)} + \left(\frac{4}{3} \frac{\sin^3 \frac{\beta}{2}}{\beta - \sin\beta} - \cos\beta \right) \frac{R^3}{2} (\beta - \sin\beta), \quad \Pi(D) = \frac{\alpha Q^2}{g \pi R^2} + yA. \quad (4)$$

Equalizing jump functions, we get

$$\frac{6\alpha Q^2}{g R^5} = \frac{[3\pi\beta - 3\pi\sin\beta - 4\sin^3 \frac{\beta}{2} - 3\cos \frac{\beta}{2}(\beta - \sin\beta)]\pi(\beta - \sin\beta)}{2\pi - \beta + \sin\beta}. \quad (5)$$

It follows from the obtained equation that to each value of $Q < Q_g$ flow running by water conduit corresponds a certain β angle and therefore a certain h_* value of a boundary depth. That is, from equation by the $Q < Q_g$ value is determined angle β

$$h_* = R \left(1 - \cos \frac{\beta}{2} \right). \quad (6)$$

The distance L_1 from the point where the jump occurs to the lower basin is determined geometrically by finding power loss of the pressure floe section.

It is not difficult to determine the above L_1 distance

$$L_1 = \frac{h_0}{i_0 - \frac{Q^2}{K^2}}, \quad (7)$$

where K is the pipe capacity.

It follows from (7) that increase of flow is accompanied by the jump point displacement to the head basin.

As far as the jump point depends on h_0 and Q moves along non-pressure section, then the boundary jump initiation probability is very small. Consequently, to determine the initial depth of the jump is reasonable to use the technique proposed in this paper which consists in finding the distance L_1 of the jump development place, then determining h_1 depth form free surface b_2 type curve equation [14].

Let us now differentiate to types of a jump which is developed in a closed channel. With this end in view we compare h_* boundary and conjugate small h_1 depths corresponding to the given flow. If $h_1 > h_*$ then call the jump approached or suppressed, and if $h_1 < h_*$ - remote, as in case of open channel. It should be noted that dividing jumps into types is not an informal action. First, let us note that kinetic energy of a rough stream in a drowned section where jumps occur is smaller than that of the removed jump section and its dissipation caused by a quiet stream is more perfect. Continuous exchange of air and fluid particles takes place

in the section of jump. In the place of the drowned jump feebly marked aeration is observed. Small air bubbles are developed in the lower part of the effective cross-section, then they moved to its top and with high velocity escape the fluid stream without being entrained by the stream, and dynamic equilibrium of air and fluid particles is established.

At the site of the remote jump relatively tiny particles of air in the form of bubbles are entrained by the fluid stream through the lower part of the section the existing large bubbles move, gradually accelerating, in the opposite direction to the surface of the jump section. As a result removed jump possesses entrainment property.

The hydraulic jump occurred in a closed canal is a dangerous phenomenon especially for open pipelines.

It causes jerks of the pipe which lead to destruction of free supports. Therefore, if a hydraulic jump is detected it is necessary to take special emergency measures to stop it. To provide smooth operation of a pipeline by a valve which will gradually close the pipe by throttling and without changing the flow, establishing pressure flow along the entire length of the pipeline.

Conclusion

The hydraulic jump occurred in a closed canal is a dangerous phenomenon especially for open pipelines.

It causes jerks of the pipe which lead to destruction of free supports. Therefore, if a hydraulic jump is detected it is necessary to take special emergency measures to stop it. To provide smooth operation of a pipeline by a valve which will gradually close the pipe by throttling and without changing the flow, establishing pressure flow along the entire length of the pipeline.

Conjugate depths of the closed canal hydraulic jump are conjugate only in case of boundary jump. Depending on the value of existing overpressure at the lower end canal the point where a jump occurs undergoes an essential displacement along the canal. In case of removed jump the fluid stream possesses entrainment property. Jump elimination without the flow change is possible by throttling of the valve.

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ՓԱԿ ԿՏՐՎԱԾՔՆԵՐՈՒՄ ՀԻՂՐԱՎԼԻԿԱԿԱՆ ԹՈՒՉՔԻ ԱՌԱՋԱՑՄԱՆ ՏԵՍԱԿԱՆ ԵՎ ՓՈՐՁԱՐԱՐԱԿԱՆ ՈՒՍՈՒՄՆԱՍԻՐՈՒԹՅՈՒՆՆԵՐ

Մարիաննա Պողոսի Հակոբյան

*Ճարտարապետության և շինարարության Հայաստանի ազգային համալսարան, ք. Երևան, ՀՀ
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Հոդվածում ուսումնասիրվում են խողովակաշարերում հիդրավլիկական թռիչքի առաջացման պայմանները, դրանց տեսակները և առավել հանդիպող տեղերը: Ներկայացվում է համալուծ խորությունների կապի որոշման տեսական մեթոդը, ինչպես նաև դրա ազդեցությունը խողովակաշարում հիդրավլիկական ռեժիմի վրա: Ինքնահոս խողովակաշարերում կարող են առաջանալ ոչ ճնշումային, ճնշումային և խառը հիդրավլիկական ռեժիմներ: Ճնշումային ռեժիմից ոչ ճնշումայինի անցումը տեղի է ունենում սահուն, մինչդեռ հակառակ անցումն ուղեկցվում է ազատ մակերևույթի խզումով, որը նման է բաց հուններում հիդրավլիկական թռիչքին: Նշված ելքի դեպքում թռիչքի դիրքը կախված է միայն հոսքի չափից. ելքը մեծանալու դեպքում թռիչքը տեղափոխվում է վերև՝ հոսանքի ուղղությամբ: Փակ կտրվածքներում՝ խողովակներում, հիդրավլիկական թռիչքի վարքագիծը և դրանցից առաջացող հոսանքի խեղդումը բավարար չափով ուսումնասիրված չեն, սակայն տեսությունն ու փորձերը ցույց են տալիս հուսադրող համապատասխանություն: Այս վերլուծությունը չափազանց կարևոր է բազմաֆունկցիոնալ ջրատարների համար, որտեղ էներգետիկ կիրառությունների առումով նախընտրելի են ոչ ճնշումային հատվածները:

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ТЕОРЕТИЧЕСКИЕ И ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ГИДРАВЛИЧЕСКИХ ПРЫЖКОВ В ЗАКРЫТЫХ СЕЧЕНИЯХ

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В статье рассматриваются условия формирования гидравлических прыжков в трубопроводах, их виды и характерные места возникновения. Представлен теоретический метод определения связи между сопряжёнными глубинами и её влияние на гидравлический режим трубопровода. В самотечных трубопроводах могут наблюдаться безнапорный, напорный и смешанный режимы течения. Переход от напорного к безнапорному происходит плавно, тогда как обратный переход сопровождается разрывом свободной поверхности, аналогичным гидравлическому прыжку в открытых каналах. При заданном расходе положение прыжка зависит только от величины потока: с его увеличением прыжок смещается вверх по течению. Поведение гидравлических прыжков и вызываемое ими сужение потока в круглых трубах изучены недостаточно, хотя сравнение теории с экспериментальными данными показывает обнадеживающее соответствие. Анализ особенно важен для многоцелевого использования водоводов, где для энергетических целей предпочтительны участки с безнапорным режимом.

Ключевые слова: *трубопровод, смешанный режим, сопряжённая глубина, воздушная полость, поток*

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