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# ANALYSIS OF PRESSURE LOSSES IN CONVENTIONAL HYDRAULIC MANIFOLDS BLOCKS. A REVIEW

BY

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**Abstract.** The hydraulic manifold blocks (HMB) are the main components of hydraulic systems. One main problem is the loss of hydraulic energy during operation, which might be as high as 50%. Another problem is the large weight. The scientific literature mentions two research pathways, to solve such issues. The first focuses on conventional HMB constructed by machining process, applied to different configurations. The second focuses on methods to reduce the weight and the energy loss by using additive manufacturing (AM) or laminated blocks (LB). This paper refers only to conventional HMB. The scientific literature usually uses Ansys to estimate the hydraulic energy losses and validates the findings by experiments. Results of significant investigations focusing on the 90º connections, expansion connections, contraction connections, offset connections of holes, V elbows with different angles are discussed in the present paper.

**Keywords:** Hydraulic manifold blocks, pressure loss, weight reduction, ANSYS.

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## 1. Introduction

The hydraulic manifold blocks (HMB) are among the most widespread components of the hydraulic systems. They are used as bodies of directional control valves, pressure valves and flow control valves, as well as for various complex applications that require the incorporation of valves, sensors, etc. Conventional hydraulic blocks are obtained by casting, forging, extrusion followed by machining of interfaces and inside channels.

The studies on hydraulic blocks show that the hydraulic efficiency can be in the range from 9% to 60%, because of the pressure losses that occur, when the fluid circulate at high pressure and/or high velocity inside the block. Research on the mobile applications indicate that the average efficiency is 21%, meanwhile research on industrial applications indicate that the average efficiency is 50% (Love *et al*., 2012). The hydraulic losses in the hydraulic blocks are generated at the intersection of two channels and along the channels. According to the work „Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry", elaborated by Lonnie Love et al., a typical mobile hydraulic system has an overall hydraulic efficiency of approximately 14%, within the process of transmission of power, from the source to the cylinder. The calculus took into consideration the pump losses, the source losses, the hydraulic hose losses and the valve losses that can be as large as 43% (Love *et al*., 2012).

Another problem of hydraulic blocks is the weight. A study carried out by NASA, (Spitzer, 1984), shows that the embedded hydraulic components accounted for 9.5% of the fuel used on an aircraft during flight and ground operations (Love *et al*., 2012). Lonnie Love et al., in their paper, showed that the hydraulic and pneumatic components account for an average of 0.98% of an aircraft's weight (Love *et al*., 2012). The high weight of the hydraulic blocks is due to the large volume of material necessary to build the semi-finished block, after the machining of the interfaces and the channels result a large volume of material without any engineering functional role in the unmachined areas.

In this context, the optimization of hydraulic blocks is important for the industry and many studies on the methods to reduce the hydraulic losses and/or to reduce the weight of the blocks, were published. In this paper, the state of the art concerning the pressure losses within the conventional hydraulic blocks is discussed.

The present paper presents an overview of the research conducted in the area of pressure drop in hydraulic manifolds block and focuses on methods of investigation used.

## 2. Classification

The studies regarding the pressure losses within the hydraulic blocks can be classified in two main research directions, presented in Fig. 1. The first focuses on the conventional hydraulic blocks obtained by machining to obtain different architectures of connections. The second research direction focuses on identification of new technological processes to obtain hydraulic blocks with special geometries able to generate reduced pressure losses, as well as keeping the same technical performances by using lower volume of material in order to reduce the weight.

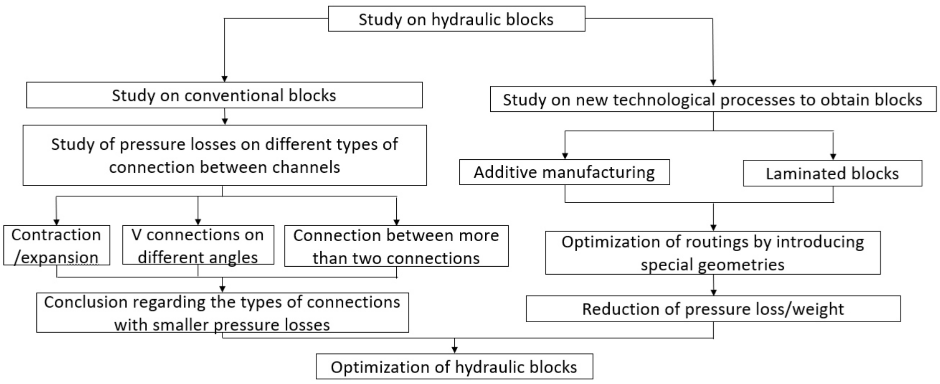


Fig. 1 – Research domains regarding HMB.

Other types of research works aim to implement AI in the design phase of the blocks by using mathematical algorithms to identify the optimum position and type of the components (Liu *et al.*, 2008) and/or the best routing to obtain a compact designs (Hu *et al.*, 2019). In the paper „Automated AI-based mechanical design of hydraulic manifold blocks" the authors propose a script based on AI to help the designers to model the CAD of hydraulic blocks by the identification of the optimum architecture of components and channels, from the design phase (Chambon and Tollenaere, 1991).

## 3. Analysis of research results obtained by numerical simulations and experiments

The studies on conventional hydraulic blocks present different solutions from the most common to the high efficient type providing minimum pressure losses between connections. As a result reccomendations on the optimal types of connections that can be used in the design phase of the hydraulic blocks, were provided. The pressure losses for the main connections between channels studied in the papers published by Zardin et al. (2017a; 2017b) and Zhang et al. (2019) are calculated for the following types:

- 90° connections:
    - Simple connections: L, T, T-reverse şi X, Fig. 2;
    - Expansion connection (the flow is guided from a smaller diameter to a larger diameter), Fig. 3;
    - Contraction connection (the flow is guided from a larger diameter to a smaller diameter), Fig. 3;
    - Offset connections: between axis of channels or between end of a channel hole and the axis of channel with which the connection is made, Fig. 4.
- V connections, Fig. 5;

To make the contraction/expansion connection the following relation is used to calculate the larger diameter $d2=d1\cdot\delta1$, where d1 is the reference diameter (smaller one), d2 is the larger diameter and δ1 is the expansion/contraction ratio.

Zardin et al. published relevant papers regarding the pressure loss at the change of direction, in the channels of hydraulic blocks. In the first paper "Pressure Losses in Hydraulic Manifolds", the authors study the pressure loss by CFD analysis and experimental tests. The types of connections are: the 90° (L), the contraction/expansion, the offset between the end of a channel hole and the axis of channel at which the connection is done. The reference diameter (d1) of channels is 6 mm, for the connections at 90° (L) and also for contraction/expansion connections. For the offset connections, the reference diameter (d1) is changed to 9.525 mm. The distance between the end of a channel hole and the axis of channel with which the connection is done are studied for different cases: in the positive direction the distance is 0; 4.76 mm; 7.62 mm and on negative direction the distance is -2.54 mm; -4.76 mm. The domain of the fluid flow rate used for experimental tests and for CFD analysis is in interval of 5-65 l/min and the working fluid is ISO VG46 mineral oil.

The results show that the expansion connection, presented in Fig. 3 have the lowest pressure loss compared to all the other types of connections studied in this paper and presented in Fig. 2, Fig. 3, Fig. 4, Fig. 5. Higher the expansion/contraction ratio d1/d2 is, lower the pressure loss is. The ratios values d1/d2 representing the expansion connections investigated by the Zardin et al. are [1; 1.25; 1.5; 1.75; 2; 2.25; 2.5]. The contraction connections usually generate pressure losses in the same range as the 90° connections type do. For offset connections, the results show that the pressure losses are almost the same as for 90° connection, in the case studies representing the fluid moving in positive direction, while for the case studies that illustrate the moving of the fluid in the negative direction, the pressure losses are higher.

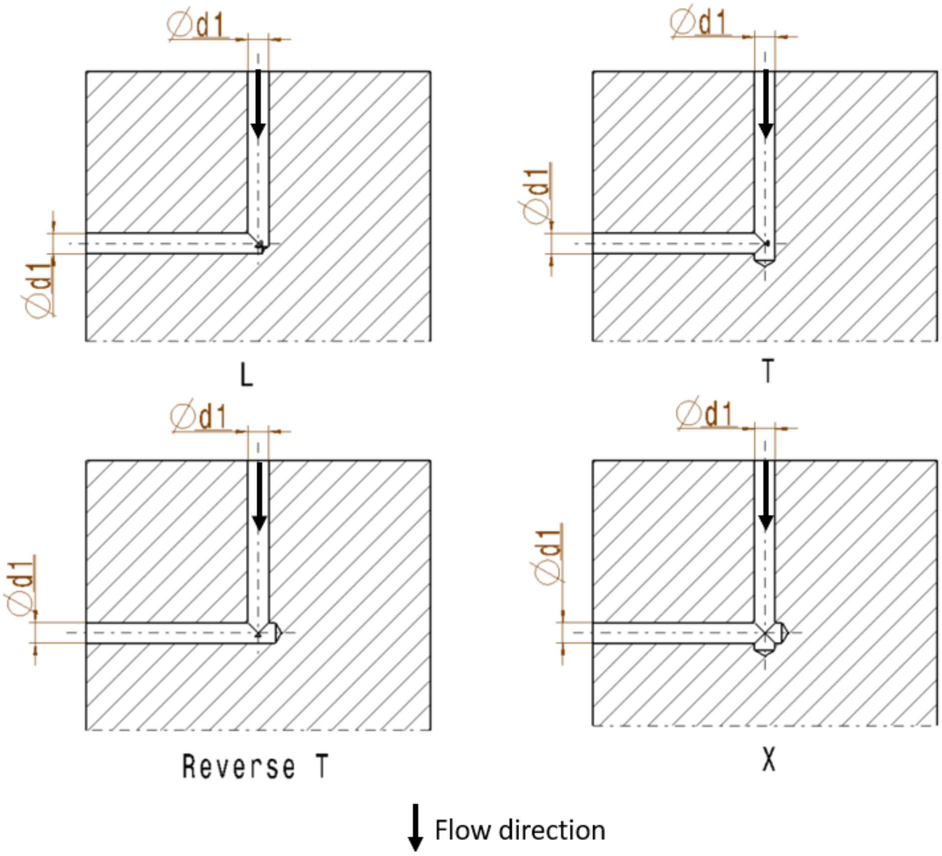


Fig. 2 – Types of intersection of channels within the 90° connections.

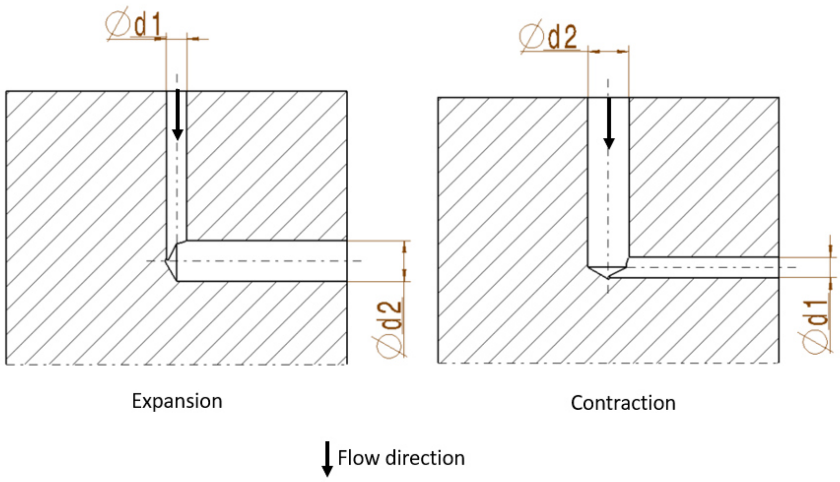


Fig. 3 – Expansion/contraction connections.

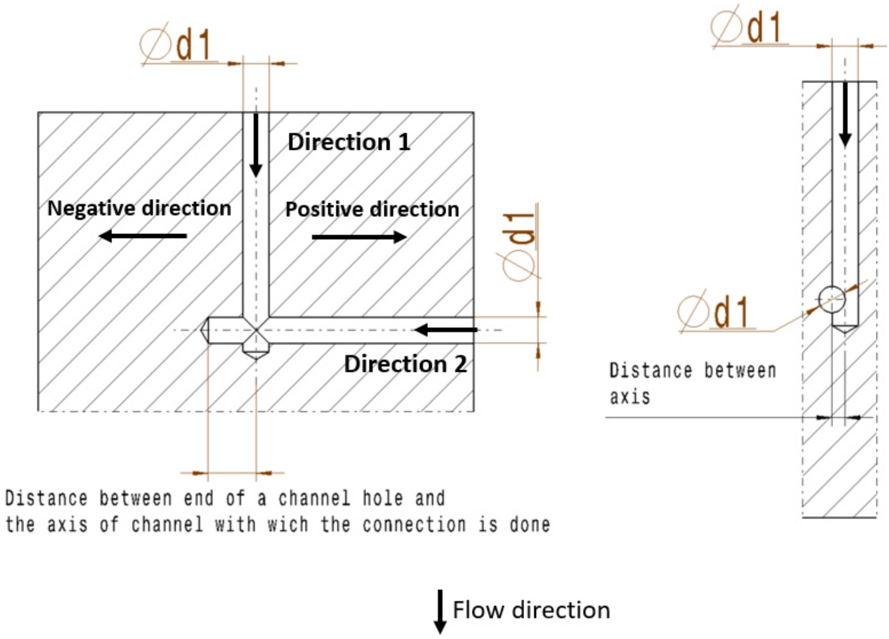


Fig. 4 – Offset connections.

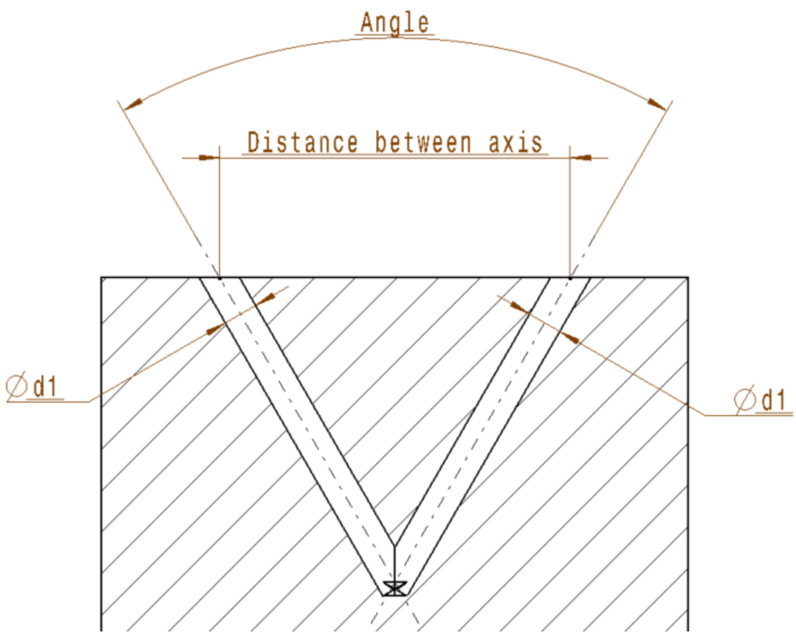


Fig. 5 – V connections.

In the second paper "*Pressure Losses in Multiple-Elbow Paths and in V-Bends of Hydraulic Manifolds"* (Zardin *et al*., 2017b) published by the same first author, the pressure losses were identified by CFD analysis for connections in V and also for connections in V with expansion/contraction of the diameter. For V connections, the study was done for the range of angles from 30° to 150°, with a step of 15°. Results are presented in Table 1.

**Table 1**
*Rates of the pressure drop versus dynamic pressure for V connections at the velocity of 10,19 [m/s]* (Zardin *et al*., 2017b)

| Angle | Distance between axis | | |
|---|---|---|---|
| | 3·d1 | 5·d1 | 10·d1 |
| 30º | 3.2 [-] | 4.2 [-] | 7.8 [-] |
| 45º | 3.5 [-] | 4.5 [-] | 8 [-] |
| 60º | 3.2 [-] | 4.4 [-] | 8.1 [-] |
| 75º | 3.2 [-] | 4.5 [-] | 8.2 [-] |
| 90º | 2.9 [-] | 4.2 [-] | 8 [-] |
| 105º | 2.8 [-] | 4 [-] | 8.1 [-] |
| 120º | 2.2 [-] | 3.3 [-] | 7.8 [-] |
| 135º | 2 [-] | 3.1 [-] | 7.9 [-] |
| 150º | 1.8 [-] | 2.8 [-] | 6.2 [-] |

The following values for the velocity within channels was obtained: 0.64 m/s; 2.55 m/s; 5.09 m/s and 10.19 m/s. Kinematic viscosity has the following values: 22 cSt, 46 cSt and 100 cSt. The distance between the axis of the channels has the following values: 3·d1, 5·d1 and 10·d1. The reference diameter (d1) is 10 mm. The study analyses the values of pressure loss at the 10.19 m/s velocity and the dynamic viscosity of 100 cSt because for the rest range of the velocities the pressure losses are almost the same, without significant changes. Moreover, at different values of viscosity the trend of pressure loss is the same. The results show that for V connections the lowest pressure losses are obtained for angles higher than 90°. The higher the distance between axis of channels lead to a higher pressure losses. The optimal distance between the axis of the channels that was recommended by the authors is up to 5·d1.

The pressure drop is non-dimensioned with respect to 1/2 $\rho v^2$, where $\rho$ is the fluid density and v is the flow velocity defined as the maximum flow rate in the tests performed over the reference flow area at the inlet of the geometry considered (Zardin *et al*., 2017a).

The research work regarding the V expansion/contraction connections, was done for the reference diameter of 10 mm, the step of angle variation was changed to 30°, the angles range remain the same, the velocity of flow 6.4 m/s, the kinematic viscosity 46 cSt, the expansion/contraction ratio from 1 to 2 with a step of variation by 0.4. The results show that the lowest value of the pressure loss was obtained for V-expansion connection at angles 150°, 90° and 30°. The value of expansion/contraction ratio seems not significantly influence on the differences between the results for each connection studied. The contraction connections have higher pressure losses than the expansion connections.

In the paper *3D Printing for Energy-Saving: Evidence from Hydraulic Manifolds Design"*, Zhang et al. present the pressure losses obtained by CFD analysis and experimental tests for connections at 90°: L, T, T-reverse and X, expansion/contraction connections and offset connections between axis of channels. The reference diameter (d1) is 6 mm. The values of distance between axis of channels are Δ=1.2 mm; 2.4 mm; 3.6 mm. The values of expansion/contraction ratio are d1/d2=1.2; 1.5; 2 (Zhang *et al*., 2019).

The results showed that the lowest pressure losses are obtained for the expansion connections having the highest expansion/contraction ratio. Both for the expansion connections and for the contraction connections the pressure losses have the tendency to decrease when the expansion/contraction ratio increase. For the offset connections, for higher values than 2.4 mm the pressure loss has the tendency to increase, until the 2.4 mm value the pressure loss has a constant trend (Zhang *et al*., 2019).

In the paper *„Flow measurement and parameter optimization of right-angled flow passage in hydraulic manifold block"*, Hu Jian-Jun et al. studied the flow moving through the 90° connections by CFD analysis and by experimental tests. The particularity of this paper is that it focuses on discussions on the cavities at the intersection of channels that do not have any functional role, they exist as a consequence of tolerances to cover uncontrollability machining. Different types of geometries with different types of intersection of channels studied by Hu et al. are presented in the Fig. 6. The diameter of the channels is 21 mm. The studied cases can be classified in two categories: first type (cases a, b, c from Fig. 6) with the cavities oriented in the flow direction and the second type (cases d, e, f from Fig. 6) with the cavities are oriented in the opposite of flow direction. Each configuration type described above depends on the length of the cavity, L (see Fig. 6). The length of cavities L have the following values for each configuration: (a) and (d) L=0, (b) and (e) L=0.2·D, (c) and (f) L=0.5·D, where D is denoted the diameter of channels (Hu *et al.*, 2019).

The machining process of channels is done for small diameters (up to 10 mm) and it generate several potential issues that can have as consequence the increase of pressure losses in hydraulic manifold blocks:

- the tool deflection due to the small size of tools, can generate additional machining forces;
- the difficulty to maintain tight tolerances can have as consequance minor deviation of the dimension and of the position, which is a source of for the increase of pressure losses;
- the formation of burr at the intersection of two channels motifies the boundary layer thickness, and generates additional hydraulic energy losses;

- the acces for inspecting, measurement, cleaning and deburing is limited by the small diameter of channels, which can lead to high pressure loss caused by strangulation.

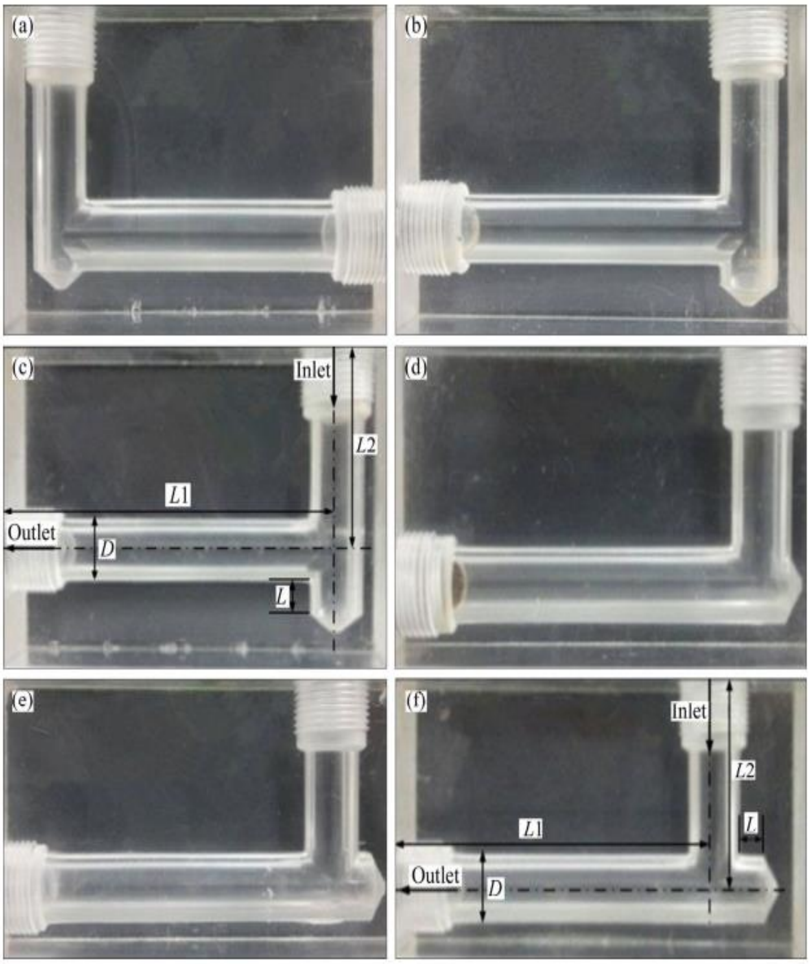


Fig. 6 – Definition of geometries for the studied connections (Hu *et al*., 2019).

In Fig. 7 the results obtained by Hu et al., by experimental tests performed by using the Particle Image Velocimetry (PIV) technology to visualize what happens into a plexiglas block are presented. It can be noticed that by increasing the length of cavities without having any functional role (noted L in Fig. 6) the vorticities from zone A will increase, and by consequace the boundary layer decreases and the pressure losses increase.

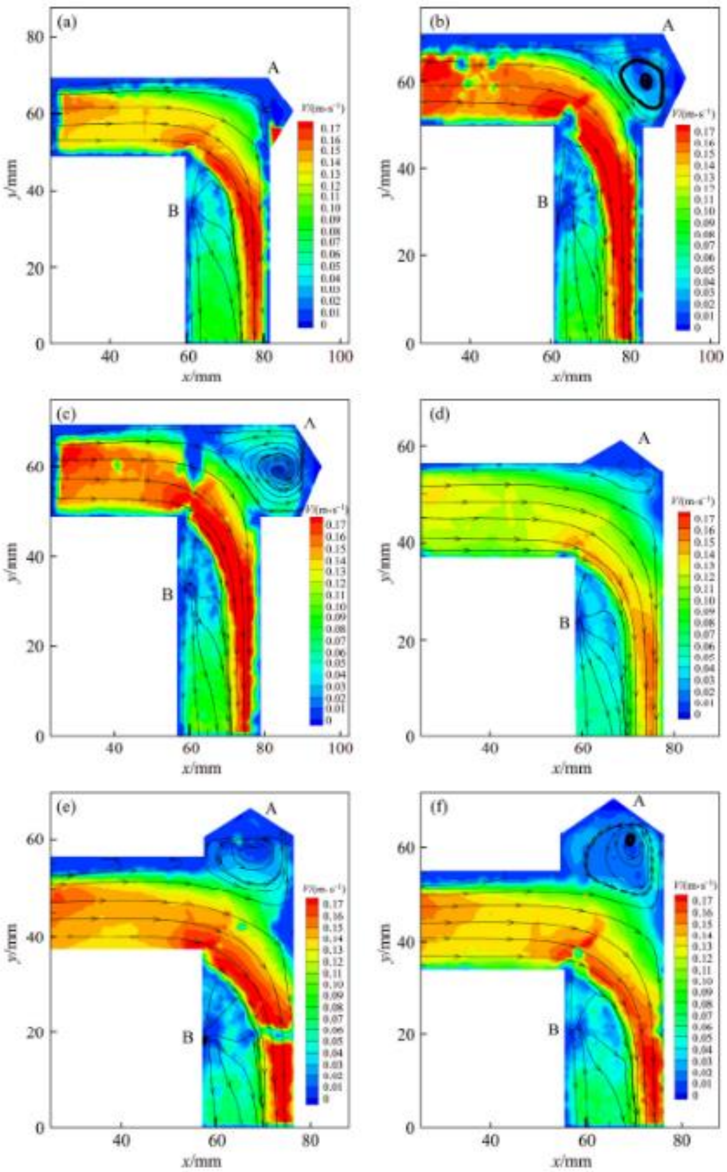

Fig.7 – Results of experimental tests by using Particle Image Velocimetry (PIV) for the flow through the studied connections (Hu *et al*., 2019)

To optimize the flow through the connections, the multiple regression analysis using the Box-Benhnken model was applied. The results of the analysis show that the pressure loss can be decreased with 11.15% for the diameter of 14.64 mm and the length-diameter ratio of cavity of 67.53%. With a similar geometry as for the case of pipes geometry with the same diameter value and a turning radius of 20 mm, a decrease of pressure loss by 64.75% was obtained (Hu *et al*., 2019).

### 4. Conclusions

The studies on conventional hydraulic blocks lead to recommendations regarding the best solutions with lowest pressure losses regarding the most types of connections of channels obtained by machining. By analysing the published works in the domain, the following conclusions can be highlighted:

1. The lowest pressure loss was obtained for the expansion connection, the next for the V connections at angles higher than 90º whether the distance between axis does not exceed the 5·d (diameter of channels), and the highest pressure losses were obtained for 90º connections.
2. To design and construct offset connections, the designers must take into consideration the following: the distance between the end of the channel hole and the axis of channel with which the connection is done, the lowest value must be 0 to avoid the increasing of pressure loss, while the distance between two axis must be at least 1/2·d (diameter of channels).

The high pressure losses from the hydraulic manifold blocks are mainly caused by the small diameter of the channels, manufactured by machining technologies. Potential problems can occur due to the tool deflection, the difficulty to maintain tight tolerances, the burrs and the limited access. These issues are difficult to control and a small deflection from nominal design can lead to high pressure losses through the routing of the channels. For instance, it can be noticed that for the offset connections with ½ d1 deviation from the nominal lead to a significant increase of pressure loss. Moreover, the paper points out of the fact that the generation of cavities without any functional role, due to issues presented above, can lead to the increase of the intensity of vortices that have effect on the increase of the pressure losses.

In mass production process of manifold hydraulic blocks, usually the diameter of the channels is the same for all channels and the tolerances are large, to allow simple machining process, but the overall hydraulic efficiency is by consequence very low. The analysis presented in this paper demonstrates that a research domain can be important, the identification of new and efficient methods to reduce pressure losses in HMB, in order to reduce energy consumption.

For having a good estimation of pressure loss based on the CFD analysis comparing to the experimental results, the following parameters and setup hypothesis should be taken in consideration:

1. To select the appropriate turbulence model – the most used turbulence model are k-ε and k-ω, with relatively small errors between CFD analysis and experimental results.

2. To use a dense mesh in critical areas, such as the connections between channels, in order to capture details regarding the velocity and the pressure modifications.
3. To take into consideration realistic boundary layer conditions, such as the measured temperature, velocity and pressure for the inlet and for the outlet section.
4. To take into consideration, the impact of the viscosity magnitude – the viscosity has a significant impact on the differences between the experimental tests and the CFD analysis.
5. To take into consideration the cavitation effects – if the cavitation effect is not take into consideration in CFD analysis, the analysed pressure drop value may be underestimate, comparing to the loss observed in experimental tests.
6. To have in view, the differences between the CAD studied by CFD analysis and the realistic experiments, due to dimensional and positional tolerances of machining. Moreover, an important element is the roughness of the internal walls that form the channels. A correct estimation of these parameters or a measurement report can help to avoid the large errors observed to occur, between the CFD analysis and the experimental results.
7. To have in view, the properties of the fluids – density, viscosity.
8. To set correctly the Convergence Criteria: For stable and reliable results, the convergence criteria must be strict, to avoid residual fluctuations. Complex flows in hydraulic channels often require stronger convergence criteria to capture the accurate pressure and velocity values.

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## ANALIZA PIERDERILOR DE PRESIUNE ÎN BLOCURI HIDRAULICE CONVENȚIONALE. STADIUL ACTUAL

(Rezumat)

Blocurile hidraulice sunt componentele principale ale sistemelor hidraulice. Principala problemă a blocurilor hidraulice convenționale este pierderea mare de energie hidraulică în funcționare, care poate ajunge până la 50%. Altă problemă este greutatea mare. Literatura științifică menționează două direcții de cercetare pentru a rezolva aceste probleme. Prima se concentrează pe blocurile hidraulice convenționale, obținute prin prelucrări mecanice pentru o obține diferite configurații de conexiuni. Al doilea tip de lucrări s-a focusat pe reducerea greutății și a pierderilor de energie prin utilizarea tehnologiilor de fabricație aditivă şi a blocurilor laminate. Această lucrare se referă numai la blocurile hidraulice convenționale. Literatura de specialitate în majoritatea cazurilor utilizează Ansys pentru a estima pierderile de energie, iar validarea estimărilor se realizează prin teste experimentale. Lucrarea de față se focusează pe rezultatelor unor investigații semnificative axate pe conexiuni la 90º, conexiuni de tip expansion, conexiuni de tip contraction, conexiuni cu decalaj, conexiuni în V cu diferite unghiuri.