Test bench of head losses in incompressible flow

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Abstract

The main goal of this project was the development of an automated test bench of head losses, with an intuitive graphical interface that aims to be easy used as a learning tool by the students in the Fluid Mechanic I course.

A software was developed using MATLAB® that handles the data recorded and sent by the hardware. The goal of this software is to display to the user, through a graphical interface, the pressures read from the sensors, the flow rate measured, as well as several relevant results regarding the study of pressure drop. The characteristics and parameters of these studies are also shown.

Keywords: Head losses; Pressure drop; Friction factor; Moody's diagram; Design; Data acquisition; MATLAB.

1. Introduction

Information regarding head losses that occur in pipes, as well as in different hydraulic fittings, is crucial in the design and sizing of pipe systems. The test bench presented aims to determine the friction factor in pipes with distinct diameters and levels of roughness, in order to study the head losses in different types of valves and fittings, while comparing different methods of flow measurement. Both the execution of the test bench and the data acquisition process are controlled through a computer, using the developed software.

Whenever there is a flow of fluid through of a pipe, friction occurs between the fluid and the pipe wall, regardless of the flow being laminar or turbulent. In general, a consequence of this effect is the decrease in pressure inside the pipe as the fluid goes over it. These decreases in pressure are known as head losses.

The study of flow pipes requires different sorts of calculations. For an appropriate analysis of the flow occurring in a pipe, it is important first to determine whether the flows are laminar or turbulent, as different methods and equations are used in each case [1]. Laminar flow occurs in situations where the fluid flows at reduced velocity and with high viscosity. Turbulent flow, on the other hand, is characterized by turbulence and a mixture in the flow, typical in situations where the flow occurs at high velocity and with reduced viscosity.
The type of flow can be evaluated using Reynolds number (Eq.(1)),

\[
Re = \frac{\rho V d}{\mu} = \frac{Vd}{\nu}, \tag{1}
\]

where \(\rho\) refers to the specific mass of the fluid [kg/m\(^3\)], \(\mu\) is the dynamic viscosity [Ns/m\(^2\)], \(V\) is the average velocity of the flow [m/s] and \(d\) is the inner diameter of the pipe [m].

For values of the Reynolds number less than 2100, the flow is considered to be laminar, while for values bigger than 4000 it is considered to be turbulent. In the regime between these two values, the flow is considered to be transitional.

2. Equations required for the design of test bench

2.1. The entrance length and fully developed flow

In an internal flow, the effects of viscosity increase along the ducts, due to the limitations of the walls. For a finite distance, a boundary layer develops, making the flow completely developed viscous, such that there is no variation of velocity beyond a certain distance. This distance is important, because Darcy-Weisbach equation, discussed in the next section, can be applied to the fully developed portion of the pipe flow.

The required distance for development of the flow is known as entrance length \((L_e)\), which can be estimated if Reynolds number is known.[3][4]

For the case of laminar flow:

\[
\frac{L_e}{d} = 0,06 Re \tag{2}
\]

And for the case of turbulent flow:

\[
\frac{L_e}{d} = 4,4 Re^{1/6} \tag{3}
\]

It is important to take into account the effects of the entrance region, because if neglected the pressure drop might be wrongly perceived as head loss.

2.2. Calculation of head losses

The head losses of flow in an installation depend on the flow rates as well as on the type of material and the dimensions of the pipes. Therefore, several equations were proposed in order to calculate these values, such as the Darcy-Weisbach equation and the Colebrook-White correlation.

2.3. The Darcy-Weisbach Equation

The Darcy-Weisbach equation is the foundation to the calculating of head losses in fluid flow in pipes. The equation is as follows:

\[
h_f = f \frac{L V^2}{d 2g}, \tag{4}
\]

where \(L\) is the length of the pipe [m] and \(d\) its diameter [m], \(V\) is the mean flow velocity [m/s], \(f\) is the friction factor and \(g\) is the acceleration of gravity (9,81 m/s\(^2\)). The value of \(h_f\) represents, therefore, the
frictional pressure drop for a flow at velocity \( V \) through a pipe of length \( L \) and diameter \( d \).

2.4. Friction factor

The friction factor \( f \) is dimensionless, and it can be determined through semi-empirical correlations, which are a function of the Reynolds number and the ratio \( \varepsilon/d \), where \( \varepsilon \) stands for the roughness of the pipe [5].

For cases of laminar flow, the expression of the friction factor is derived from the relationship between the Darcy-Weisbach equation and the Hagen-Poiseuille equation (Eq. (5)).

\[
h_f = \frac{32 \mu L V}{\rho g d^2}
\]  

(5)

This equation shows that, for laminar flow, the head loss changes linearly with velocity, although the length and diameter of the pipe, as well as the viscosity and the specific mass of the fluid, also influence the head loss.

Therefore, it is straightforward to get to the expression of the friction factor for the cases of laminar flow, based solely on Reynolds number (Eq. (6)).

\[
f = \frac{64}{Re}
\]  

(6)

For the cases of the turbulent flow, the friction factor is initially estimated through the empirical expression shown in Eq. (7).

\[
f = \frac{0.316}{Re^{1/7}}
\]  

(7)

With this value, and through an iterative process, we can determine a new value by using Colebrook’s correlation (Eq. (8)).

\[
f = \left[-2 \log \left( \frac{\varepsilon/d}{3.7} + \frac{2.51}{Re^{1/7}} \right) \right]^{-2}
\]  

(8)

This correlation provides a good representation for the variation in the friction coefficient for turbulent flow, and it is the basis for creating the Moody diagram.

2.5. Minor losses

Up until now, head losses along a pipe have been considered. However, minor losses, be it due to changes in direction, diameter transitions or the presence of accessories, should also be taken into account. Flow separation, for instance, is caused by accessories, resulting in the generation and dissipation of turbulent eddies [5]. These minor losses can surpass the frictional losses, and are represented by Eq. (9):

\[
h_m = K \frac{V^2}{2g},
\]  

(9)

where \( h_m \) is the head loss for an accessory, and \( K \) is the loss coefficient related with that accessory. Table Tab. 1 shows the typical values for \( K \) for various types of accessories.

<table>
<thead>
<tr>
<th>Component/Fitting</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Valve</td>
<td>0.05</td>
</tr>
<tr>
<td>Angle Seat Valve</td>
<td>2</td>
</tr>
<tr>
<td>Gate Valve</td>
<td>0.17</td>
</tr>
<tr>
<td>Diaphragm Valve</td>
<td>2.30</td>
</tr>
<tr>
<td>Elbow 90°</td>
<td>0.90</td>
</tr>
<tr>
<td>Elbow 45°</td>
<td>0.40</td>
</tr>
<tr>
<td>Tee</td>
<td>1.80 (aprox.)</td>
</tr>
<tr>
<td>Fork Plumbing</td>
<td>1.30</td>
</tr>
<tr>
<td>Filter</td>
<td>10</td>
</tr>
<tr>
<td>Venturi</td>
<td>2.50</td>
</tr>
<tr>
<td>Orifice</td>
<td>5</td>
</tr>
</tbody>
</table>

For the design and sizing of installations, the loss coefficients associated either with diameter transitions or with entrances and
exits, can be determined either by using equations or by analyzing data available in the literature, such as in reference [4] [5]. The head losses induced by directional changes are bigger than simple frictional losses, as they inflict separation of flow in the walls, which is the result of dynamic shocks and changes of forces over the fluid.

### 2.6. Total Head Loss

In order to determine the total head loss and the pressure drop in a system, it is necessary to apply the equation of mechanical energy in incompressible flows, by considering every parcel contributing for the variation in pressure, as in Eq.(10),

\[
\left(\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1\right) - \left(\frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2\right) = h_f + h_m - H_p
\]

(10)

in which \(h_f\) stands for the head loss due to friction of the flow in piping, \(h_m\) is the value for the minor losses throughout the flow, and \(H_p\) is the energy supplied by the pump.

### 2.7. Calculation of flow rate from pressure drop

Flow rate can be determined through the pressure drop caused by the flow passage in some accessories, such as the Venturi. These calculations include applying of the continuity equation, Eq.(11), and the energy equation, Eq.(12), in frictionless flow.

\[
Q = A_1 V_1 = A_2 V_2
\]

(11)

\[
\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2
\]

(12)

The continuity equation results from the principle of mass conservation. According to this principle, in a permanent regime, if the section of a pipe is shortened, the flow velocity must increase after going through this section [4]. In the absence of losses, if the kinetic energy is increased, then the energy resulting from the pressure decreases. The following equation shows how the mean flow velocity in a pipe can be represented as a function of the pressure drop.

\[
V_1 = \frac{A_2}{A_1} V_2
\]

\[
V_2 = \sqrt{\frac{2 (p_1 - p_2)}{\rho \left(1 - \left(\frac{A_2}{A_1}\right)^2\right)}}
\]

(13)

2.8. Systems of pipes

In this section, a comparison is made between the changes in pressure occurring in serial and parallel pipe systems. In serial pipe systems, for steady and incompressible flow, the flow rate is constant throughout the system, as shown in Eq.(14):

\[
Q_{\text{total}} = d_1^2 V_1 = d_2^2 V_2
\]

(14)

where \(d_1, d_2\) and \(V_1, V_2\) are, respectively, the values for diameter [m] and velocity of flow [m/s] in extensions 1 and 2 of the piping system. The total head loss equals the sum of head losses in each section.

\[
h_f = h_{f,1} + h_{f,2} + \ldots
\]

\[
h_f = \sum K \frac{V^2}{2g} + \sum K \frac{V^2}{2g} + \ldots
\]

(15)

For a parallel system of pipes, the flow going inside the system equals the sum of the flow passing through each individual section.

\[
Q_{\text{total}} = Q_1 + Q_2
\]

(16)
The pressure drop in a parallel system is equivalent to the pressure drop in each individual segment occurring in parallel:
\[ \Delta p = f_1 \frac{L_1}{d_1} \rho \frac{V_1^2}{2} = f_2 \frac{L_2}{d_2} \rho \frac{V_2^2}{2} \] (17)
where \( f_1 \) and \( f_2 \) are the friction coefficients of the pipes in sections 1 and 2, \( L_1, L_2, d_1 \) and \( d_2 \) are the pipes characteristics, and \( V_1 \) and \( V_2 \) are the flow velocity [m/s] for extensions 1 and 2, respectively.

2.9. Pump

A centrifugal pump is a machine that adds energy per unit of weight, for a fluid that is drained. This energy per unit of weight for a fluid \( H_p \) is known as net head. In order to dimension a pump in a given system, we need to use the energy equation and the data obtained from a supplier. As an example, considering two sections, one at the surface of the reservoir and the other in the output of the system, a control volume is obtained, which is represented by the equation (10) \([6][7]\).

After the calculation of the net head, equation (18) can be used to determine the pump power that should be used to elevate a flow of quantity \( Q \) to a net head of height \( H \),
\[ P = \frac{\rho g Q H}{\eta} \] (18)
where \( \rho \) is the specific mass of the fluid [kg/m\(^3\)], \( g \) the acceleration of gravity (9.81 m/s\(^2\)), \( Q \) the fluid flow rate [m\(^3\)/s], \( H \) net head [m] and \( \eta \) the efficiency of the pump.

3. Implementation

The following sections discuss the materials used for building the piping test bench, which include the pipes, fittings and measuring instruments.

3.1. Materials Used

Four types of materials were used for the pipes with different internal diameters (Tab. 2).

<table>
<thead>
<tr>
<th>Material</th>
<th>( D_{\text{int}} ) [mm]</th>
<th>( \varepsilon ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless</td>
<td>26.4; 16.6;</td>
<td>0.045</td>
</tr>
<tr>
<td>Steel</td>
<td>8.4; 4</td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>27.2; 17</td>
<td>0.005</td>
</tr>
<tr>
<td>Copper</td>
<td>16; 4</td>
<td>0.0015</td>
</tr>
<tr>
<td>Acrylic</td>
<td>8; 4</td>
<td>Hydrodynamically smooth</td>
</tr>
</tbody>
</table>

Regarding the accessories, in addition to the usual connecting accessories for the pipes, several valves for different functions were used. Ball valves and electrovalves are used as entrance valves in each installation line. Spring check valves are at the end of each line. In order to study head losses, the valves installed in the circuit were gate, angle seat and diaphragm valves. Additional accessories were also installed, including a filter, a Venturi and an orifice place.

3.2. Instrumentation

For the operation of this test bench, measures of the flow rate and in pressures at the several pressure points are necessary. As such, a variable area flowmeter (rotameter), two turbine flowmeters and eight pressure sensors were installed. The operation of the rotameter is based on the principle of
variable area, allowing the flow stream to increase the area of passage of the liquid and moving the float through the pipe [8]. Turbine flowmeters use the fluid’s mechanical energy to spin a rotor. Its blades transform the energy of the stream flow into rotational energy and the rotor spins proportionally to the velocity of the fluid. The signal transmission is performed using a Hall Effect sensor [8]. Flow determination can also be achieved using the differential pressure flowmeter, resorting to the Venturi and the orifice plate.

The measuring ranges of the instruments are shown in Tab. 3.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine flowmeter 1</td>
<td>1 ~ 120 [l/min]</td>
</tr>
<tr>
<td>Turbine flowmeter 2</td>
<td>0.3 ~ 6 [l/min]</td>
</tr>
<tr>
<td>Pressure Sensor 1 to 4</td>
<td>15 [psi] (1034 [mbar])</td>
</tr>
<tr>
<td>Pressure Sensor 5 to 8</td>
<td>5 [psi] (345 [mbar])</td>
</tr>
<tr>
<td>Rotameter</td>
<td>400 - 4000 [l/h]</td>
</tr>
</tbody>
</table>

Tab. 3 - Measuring range of instrumentation

4. Control and Data Acquisition

The combination of components, such that they are able to function in a consistent and coordinated way, is defined as an interface. Each component should not only perform its task, but also work together with the other components [9]. Because there are several inputs allowed by the sensors and actuators, and due to the demands of the remaining instrumentation system, it is often necessary to condition the signal, correcting or adjusting the tension levels between two consecutive components of the system. Because a computer usually works in the range between 0 and 5 V, it is often necessary to adapt the output values of sensors to this range, as well as to the range allowed by the data visualization system, in order to optimize its use [10].
4.1. Hardware

In Tab. 4 are presented the list of components used for the automation of the circuit.

Tab. 4 - Components list for control and data acquisition

<table>
<thead>
<tr>
<th>Components</th>
<th>Quant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrovalves</td>
<td>12</td>
</tr>
<tr>
<td>Flowmeter</td>
<td>2</td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>8</td>
</tr>
<tr>
<td>Arduino Uno</td>
<td>1</td>
</tr>
<tr>
<td>8 channel relay module</td>
<td>2</td>
</tr>
<tr>
<td>Data acquisition unit</td>
<td>1</td>
</tr>
<tr>
<td>Power Supply</td>
<td>2</td>
</tr>
<tr>
<td>Transformer</td>
<td>1</td>
</tr>
</tbody>
</table>

As the supply voltage of electrovalves is 24VAC, it was necessary to use a transformer of 230VAC/24VAC +/-1Amp. For the same reason, and in order to connect the valves with the computer (through the data acquisition unit), two relay modules of 5 V were also used. Relays are devices responsible for the interface between equipment operating at different voltages. For this module, it was necessary to use an external power source of 5VDC +/-500mA in order to not overload the computer.

The previously mentioned turbine flowmeters have a digital output signal of variable frequency. That is, a single impulse is transmitted intermittently with constant amplitude and the information is the frequency at which the impulses are received [10]. In order to convert this signal, an Arduino Uno plate (microcontroller board with a supply voltage of 5 V) was used. The flowmeters support a voltage of 5V~24V, for a maximum current of 15 mA (5 V DC).

Regarding the sensors, the supply voltage sits between 10 and 12 VDC and so it was necessary to use a regulated power supply of 10 to 12 VDC +/-500mAmp. Acquisition of the signals received at the sensors is performed through analog inputs in NI USB-6009 unit. The channels of analog input can be configured to perform measurements using the differential inputs or through simple entries, as there are 4 channels of positive sign and 4 channels of negative sign. In our case, as 8 pressure sensors were used, these measurements are performed by simple entries.

4.2. Circuit assembly

In this section are shown some illustrative figures of the electrical connections between the different components enumerated in the previous section.

First, in Fig. 3, the assembly of the relay modules is shown, with the common relay ports indicated by the red wires. The different channels connecting the NI USB-6009 unit (using two flat cables) are also shown.

**Fig. 3 – Assembly of relay modules**

The connections of the flow meters are performed using the Arduino controller, and are shown in Fig. 4.
Fig. 4 - Implementation of the flowmeters

Regarding the pressure sensors, shielded cables were used in order to protect the transmitted signal. Small red and blue wires are used as common inputs to the several sensors (supply (+) and ground (-)), where the corresponding pins were connected with the power supply.

Fig. 5 - Assembling of the pressure sensors

As such, for some of the sensors the output pins are the red (+) and green (-) wires, while for the others the yellow (+) and black (-) were used. This type of assembly is shown in Fig. 5 and Fig. 6.

Fig. 6 - Setup of pressure sensors

Finally, Fig. 7 and Fig. 8, shows the assembly and scheme of all components. The channels of the first relay module are connected to port 0 (lines 0 to 7) in the NI USB-6009 unit, while the channels of the second relay module are connected to port 1 (line 0 to 3). The connection of the pressure sensors to the NI USB-6009 unit is made using the 8 existing analog inputs (ai0 to ai7).

Fig. 7 – Assembly of the control circuit and data acquisition modules
4.3. Software implementation

The goal of the software developed is to support the students while they are learning to apply the tests of head losses. It was intended to be of ease of use, in order to be as helpful as possible, providing an efficient performance by the students.

The software is quite useful to perform calculations regarding the coefficients of friction and head loss due to pressure variations throughout the installation. It is also possible to use it to calculate the flow rate, using the differences in pressure. Fig. 9 shows the interface of the developed software.
5. Conclusions
The current project was developed with the goal of renewing and expanding the installations of the Fluid Mechanics Laboratory of the DEM, providing a new test bench of head losses, which is controlled by software using a computer. Several different calculations were performed for the scaling and design of the installed system, in which, as a first approximation, some parameters were assumed in order to achieve the range of the installation, namely the pipe sizes and the flow velocity. After the definition of the required dimensions and materials, consultations and comparative maps were carried out for the analysis of proposals. Afterwards, and according to the materials that were acquired, the calculations were adjusted. Regarding control and data acquisition, the electrical circuits were aligned after analyzing the necessary components for the assembly and implementation of the circuit. Here, as in the previous subject, an analysis was also conducted in order to obtain a simple, efficient and practical system. The developed software is a useful tool, which can be used to execute several different tests of head losses. It allows control of the installation, as well as the overview of measurements on the diverse pressure sensors and flowmeters, whose information is used to calculate and study head losses. This project resulted in a didactic tool, which will be available to the students of Fluid Mechanics, in order to help them to study and better understand the pressure losses in hydraulic systems.

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References