Journal of Engineering Education Transformations ,
Volume 35 , No. 4 , April 2022 , ISSN 2349-2473, eISSN 2394-1707

Computational Solvers for Iterative Hydraulic loss Calculations in Pipe Systems

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Abstract —The study of fluid mechanics spans several engineering disciplines including Mechanical, Civil, Aerospace, Chemical, Environmental, Petroleum, and Biomedical Engineering. In all these disciplines, hydraulic loss calculations in pipes are extremely important. However, the iterative nature of the solution to these engineering problems makes it intricate and cumbersome to solve. Further, it gets very difficult to visualize the solutions to such iterative problems for a wide variety of cases. The current paper aims to bridge this gap by the creation of two open-source Excel-VBA based computational solvers. The first tool corresponds to the determination of the Darcy-Weisbach friction factor through the Colebrook Equation and its visualization on a Moody's chart, which can be effectively employed by engineering instructors as an active learning tool. Second, a complete tool covering all four kinds of pipe flow situations (including the iterative problems) has been developed. The developed computational tools were employed in an undergraduate Fluid Mechanics classroom and the detailed student responses were collected on ten aspects related to teaching and learning divided broadly under four categories – 'overall rating', 'student perceptions on self-learning', 'Improvement in teaching delivery', and 'recommendation for other courses'. The data collected from student responses were subjected to statistical analysis. The results of hypothesis testing and the p-value calculations clearly justify the immense usefulness of this tool in the improvement of the overall teaching-learning process of Fluid Mechanics. Finally, the developed computational tools are being hosted free on the web for the benefit of engineering instructors, learners and professionals alike.

Keywords:Pipe losses; computational tool; Fluid Mechanics; Hydraulic loss; Moody's chart; Excel VBA.

1. Introduction

Engineering applications pertaining to fluid flows are frequently encountered by engineers of several disciplines, such as mechanical, civil, aerospace, chemical, petroleum, environmental or biomedical engineering (Appanaboyina and Aung, 2004). For instance, the design and operation of water distribution networks in urban sewage systems., the heat exchanger piping system designs and the prediction of pumping power requirements, the flow

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regulation inside pipelines in the chemical industry, the transportation of crude petroleum in the long pipelines, the design of hydraulic lines in an aircraft, or even the biomedical equipment design such as syringe needles, pumps for various applications as well as Lab on a chip, etc. are some relevant problems that require an in-depth knowledge of fluids in general, and hydraulic losses in particular (Türkkan et al., 2020).

Understanding the principles of pipe flow and fluid flow and applying these principles to industrial and engineering applications, however, is a challenge for undergraduate and postgraduate students for the following reasons: the subject involves the usage of highly advanced mathematics topics such as tensor calculus, vector, and partial differential equations. Solutions to these problems are generally obtained by sophisticated experiments and complicated computations that are difficult to understand. The design of pipelines require a consideration of materials, the diameter of the pipe, length of the pipe, friction factor, and other parameters. The knowledge of pressure drop in a pipe and other piping systems dimensions are of much importance from the viewpoint of pump selection. The pressure drop in a pipe can be easily calculated using the well-known Darcy-Weisbach equation and in such a scenario, parameter calculations are optimum in the sense that the calculated parameters are those required to exactly meet the stated specifications (Boulos and Wood, 1990). However, given a pressure drop, the calculations of diameter/length of pipe and discharge are difficult owing to the requirement of repetitive calculations.

It is particularly in problems such as the pipe flow calculations, the traditional teaching methods fall far short of the mark in communicating the complex design procedures. Further, the students can't explore the cause and effect of property magnitude changes in such an engineering scenario. More so, resorting only to the conventional pen-and-paper methodology of solving such challenging engineering problems is not only cumbersome but also reveals a clear disjoint between the concurrent industrial practice and the engineering pedagogy. Evidently, there is a need for a suitable technological intervention to bridge this gap and to enable students to see the integration of computers in engineering and its practical utility in solving challenging engineering assignments. It is expected that such computational schemes such as simulation/ visualization tools may help students easily assimilate the concepts, gain the hidden insights and thus stimulate them to explore themselves, facilitating 'self-learning'.

As far as computational frameworks are concerned, there are a variety of software/ computer languages, both commercial and open-source which can be amicably employed in the solution of pipe flow problems and the visualization of the data involved, such as:

- Python
- Scilab
- Matlab
- Wolfram Mathematica
- Pyro
- Cycle Pad,etc.

In fact, there are many computational fluid dynamics (CFD) software packages available in the market, although its practical utility for an average undergraduate student of fluid mechanics is limited. This is because of multiple reasons including the high cost of the software, the requirement of high-configuration computers, and also the steep learning curve typically required to do any meaningful analysis with these software (Appanaboyina and Aung, 2004). Hence, MS Excel / VBA platform was selected for the development of a computational solver because of its user-friendly nature, low cost, and easy availability. Excel VBA helps an engineering learner to solve critical equations, scale live graphs, to learn new concepts just by changing the parameters without worrying about the errors. It can be equally utilized to stage unique engineering demonstrations and animations. The programming language of VBA allows the user to access functions beyond what is available in other Microsoft applications (Mahawar et al., 2020). Users can use the application of VBA to customize applications according to the need, such as creating user-defined functions, etc. Moreover, owing to its very user-friendly nature, a simple interface and a wide variety of specifications, it can also be used to create computerized tools (El-Bahrawy, 1997).

Considering the user-friendly nature of Excel/VBA, it helps to solve critical equations, scale live graphs, to learn new concepts just by changing the parameters without worrying about the errors. For the calculation of pipe flow parameters, two Excel workbook programs have been designed that allows the user to calculate parameters as per the requirements. While the first tool deals with the determination of friction factor using Moody's chart, the second tool consists of four types of pipe flow problems, where three parameters are known and the fourth parameter can be solved for. The paper continues with the description of the spreadsheet, some sample problems solved using the VBA tool. Finally, this tool was utilized for teaching and learning in an undergraduate Fluid Mechanics classroom and the student responses have been collected in the form of an online survey. The results have been collated and statistical analysis have been conducted to gauge the effectiveness of such a computational tool on the overall teaching-learning process.

2. Background

For a one-dimensional flow in a pipe/duct, the energy conservation equation yields that the total energy head must remain a constant, commonly referred to as the Bernoulli equation. Bernoulli equation however ignores the viscosity present in the fluid. Upon taking the viscosity of the fluid into account, the total energy head does not remain constant along the pipe length. The total energy head is given by, $H=z+ P/\rho g+ v^2/2g$, where z is the elevation of the pipe, P is the fluid pressure, v denotes the average fluid velocity, ρ represents the density of the fluid, and g denotes the acceleration due to gravity. The total head, H decreases consistently along the pipe length due to the hydraulic losses (h_L) caused by fluid viscosity. The hydraulic loss between two different cross-sections at points 1 and 2 along the pipe is given by the difference in total heads at the two points

$$h_L=H_1 - H_2$$

With the total head being calculated at points 1 and 2, engineering design for fluid motion in pipes and other closed conduits requires that head loss be expressed as a function of the fluid, its velocity, the pipe diameter, and pipe material (Brown, 2003). Such an expression to calculate energy losses is given by the Darcy-Weisbach equation:

$$h_L = f\frac{L}{D}\frac{v^2}{2g}$$

Where, v denotes the fluid velocity and L and D represent the length and the diameter of the pipe, respectively. Another term f represents friction factor, which is a function of Reynolds number and relative roughness, $f=\phi(Re,\varepsilon/D)$ and typically determined from Moody diagram (Moody, 1944) or other correlations (Colebrook et al., 1939), (Haaland, 1983) or (Swamee and Jain, 1976).

It is not easy to determine the functional dependence of friction factor on the Reynolds number and relative roughness, and much of the information present is a result of experiments conducted by many researchers since 1933. Combining all the data for transition and turbulent flows for smooth as well as rough conditions, Colebrook came up with the following relation known as the Colebrook Equation (Kudela, 2012) where ε is the pipe roughness (in mm) and Re denotes Reynolds number given as $Re= \rho vD/\mu= 4Q/\pi D\nu$, ρ,μ and ν denote fluid density, dynamic viscosity and kinematic viscosity, respectively.

$$\frac{1}{\sqrt{f}} = -2.0\log\left[\frac{2.51}{Re\sqrt{f}} + \frac{\varepsilon/D}{3.7}\right]$$

It is worth pointing out that despite few explicit correlations for both friction factor and pipe flow problems proposed by researchers in the past, even to date, the Darcy-Weisbach equation combined with the Moody diagram/ Colebrook equation is the accepted and most accurate method for calculating the energy losses that occurs in pipe due to the fluid motion, as taught in the undergraduate Fluid mechanics curriculum. When these equations are used with continuity, energy and minor loss equations, can be used for analyzing and designing the pipe systems for any fluid. In other words, above equations can tell us the capacity of oil pipeline, diameter of pipe to install or the pressure drop in the system (Brown, 2003).

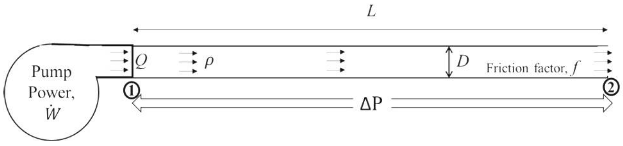


Fig. 1 : A Schematic view of the straight pipe system showing key parameters involved in engineering design.

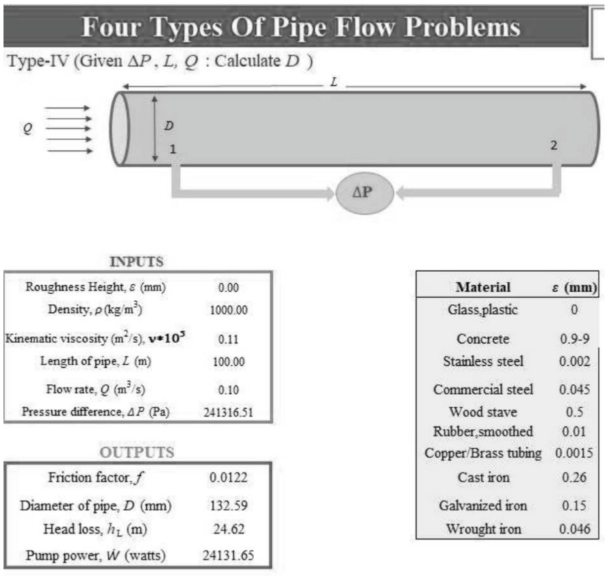
Figure 1 presents a schematic view of the straight pipe system showing key parameters involved in its engineering design such as pump power requirement

$\dot{W}$, discharge Q, density of fluid ρ, friction factor of the pipe, f, the geometrical parameters of the pipe such as L and D and finally, the pressure drop between two points 1 and 2. Typically, four kinds of problems are encountered in the design of such straight pipe systems. The first type (Type-I) of pipe flow problems usually entail the pressure drop calculations between two points at a distance L apart with D and Q being known. Type-II problems entail the determination of pipe length, L for a given ΔP,Q and D. In Type-III problem, the computation of discharge is important for a given ΔP,Q and D. Finally, in Type-IV the selection of pipe diameter D is to be done for a known ΔP,Q, and L. In all these types of pipe problems, the fundamental equation for pressure drop as given by Darcy-Weisbach is to be utilized along with a suitable way of determining friction factor, f. The friction factor can either be determined by the Moody chart or the implicit Colebrook equation. For fully developed flows in full pipes, the friction factor is a dimensionless index of the pressure drop and its correct estimation is crucial for the design of these pipes (Calomino et al., 2015). However, apart from the problems involved in solving the implicit Colebrook equation, there is another factor that should be taken into account. In Type-I and Type-II problems, given the pipe diameter, Re can be easily computed for a given fluid, and if the pipe roughness is known, f can easily be estimated from both Moody chart or by solving the implicit Colebrook equation. Subsequently, the pressure drop or length calculations could be made. However, such is not the case with Type-III and Type-IV problems, where the calculation of Re can't be done since either the velocity or the diameter of the pipe is not known. In the absence of the Re value, the determination of f by Moody diagram or by Colebrook equation is not possible. In addition, prior literature (White, 1994) has stated that the Moody Chart is only accurate to within 15%. Hence, it should suffice to say that the practical design of such an engineering problem is beset with many challenges which include iterative calculations, and conventional approaches to solving these problems involves many trials and tedious computations (Swamee and Jain, 1976). This may just imply that engineering instructors may not be able to train the graduate with such skillsets if they were to restrict themselves to pen-and-paper calculations. However, such design problems become extremely handy if computational interventions are suitably designed and implemented, and may facilitate engineering instructors to better equip their graduates with skills to solve such problems, to make effective classroom demonstrations, to give the students a 'feel' of the actual design parameters as well as to equip them with the understanding of integration of computers in solving such engineering design challenges, a much required skillset for industry. Hence, the current study proposes two computational solvers for this purpose: first, a computerized Moody chart solver for the determination of f. And second, a comprehensive tool that analyzes all four kinds of pipe-flow problems. All the types of pipe-flow problems are supplemented with a sample problem, which demonstrates the efficacy of solving such challenging and cumbersome engineering design problems at the click of a button.

However, there is a minor caveat that warrants mention. These computational tools are in no way a 'replacement' for the pen-and-paper calculations which are a must to ensure student learning. These computational tools may serve as perfect instruments of 'self-learning' where students can explore the effect of parametric variations, and also validate their pen-and-paper calculations. The instructors may also use these for active learning demonstrations inside the classroom or tutorial sessions. Further, it is overtly expected that the usage of such tools will stimulate students to learn the Goal-Seek and other ways to solve such iterative engineering problems.

3. Description Of The Computational Solvers

As mentioned in the previous section, two distinct computational solvers have been developed on the



Four Types Of Pipe Flow Problems

Type-IV (Given ΔP, L, Q : Calculate D)

INPUTS

Roughness Height, ε (mm)	0.00
Density, ρ (kg/m^3)	1000.00
Kinematic viscosity (m^2/s), $\nu * 10^5$	0.11
Length of pipe, L (m)	100.00
Flow rate, Q (m^3/s)	0.10
Pressure difference, ΔP (Pa)	241316.51

OUTPUTS

Friction factor, f	0.0122
Diameter of pipe, D (mm)	132.59
Head loss, h_L (m)	24.62
Pump power, $\dot{W}$ (watts)	24131.65

Material	ε (mm)
Glass,plastic	0
Concrete	0.9-9
Stainless steel	0.002
Commercial steel	0.045
Wood stave	0.5
Rubber,smoothed	0.01
Copper/Brass tubing	0.0015
Cast iron	0.26
Galvanized iron	0.15
Wrought iron	0.046

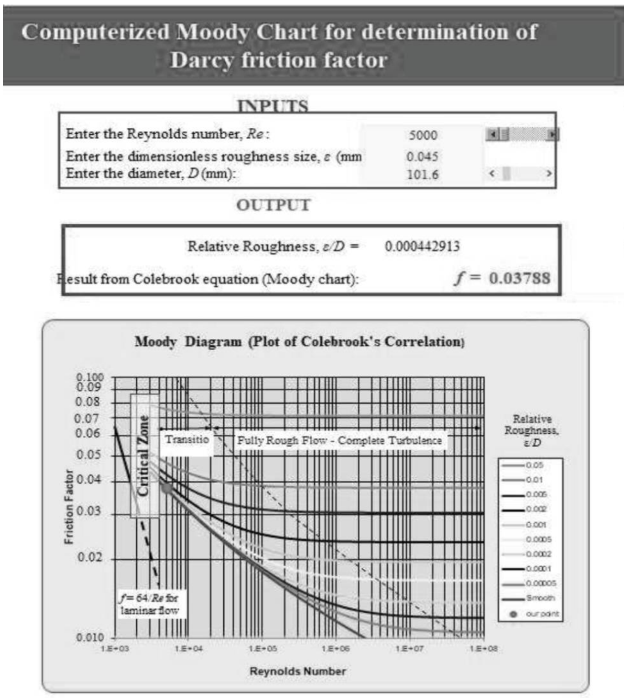
Fig. 3 : Interface of pipe flow tool Solver as uploaded on the tools website https://www.drkarnteaching.com/

Excel VBA platform. The first one pertains to the computation of friction factor, and may be particularly relevant to the Type-I and Type-II fluid problems in pipe flows.

Figure 2 shows a schematic of the computerized Moody chart solver for the computation of the Darcy friction factor, which can be downloaded from https://www.drkarnteaching.com/ by the engineering students, instructors, or professionals for the design of pipe flow systems. As the figure shows, the tool seeks three inputs : Reynolds number (Re), dimensional roughness height (in mm) and the diameter of the pipe. Reynolds number calculations for different fluids and at different temperatures can be easily obtained from the 'Fluid Property Calculator' tool by the authors from the same website. In addition, a table in the tool provides the range of roughness height for a variety of materials so that user may easily select and plug the right values in the inputs column. Upon feeding these desired inputs, the solver performs two tasks: first, it computes the Darcy friction factor value from the implicit Colebrook Equation and more importantly, it displays the same on a Moody diagram for visualization. Figure 2 demonstrates how the Moody diagram shows lines of different non-dimensional roughness in different colors, the regions of laminar, turbulent flow and a critical zone and a conspicuous red dot which shows the friction factor value for the chosen conditions. The tool does not merely compute the friction factor but also helps to visualize the regime of flow at the chosen conditions. This is of course, extremely helpful in providing a comprehensive parametric variation of the friction factor with Re in different regimes such as laminar flow or fully developed turbulent flows. Interestingly, a user can easily study parametric variations in the friction factor by tracing the location of the red dot marker, as the slider bar on Reynolds number is scrolled to the right, at a fixed pipe diameter providing for the effect of an increase in velocity alone. Conversely, a user can keep the Re fixed, and analyse the effect of increments in pipe diameter. In both the cases, it is interesting to note how the value of the friction factor 'jumps' during the transition from laminar to turbulent flows.

Next, Figure 3 presents the interface of the pipe flow solver. The computational tool comprises of four sheets, corresponding to four kinds of pipe flow problems. Each sheet offers its unique set of inputs and outputs, and also features a tabulation of the roughness height for different materials, to aid the user in entering it. For instance, Figure 3 depicts the solution of a Type-IV pipe flow problem, which entails the determination of pipe diameter, given the pressure drop ΔP, the length L of the pipe, and the discharge Q. Apart from these three inputs, the inputs table seeks fluid properties such as density and kinematic viscosity of the fluid and also the roughness height of the pipe. Subsequently, the tool calculates the corresponding value of friction factor f , pipe diameter D, required pump power and also the head loss in the process. For the purpose of verification, a sample problem from a textbook is also appended for each type of flow problem. Also, the basic equations used in the solutions of pipe flow problem are listed below (Demir et al., 2018):

$$\Delta P = \left(\frac{8}{\pi^2}\right)\rho f \left(\frac{L}{D^5}\right) Q^2$$



Computerized Moody Chart for determination of Darcy friction factor

INPUTS

Enter the Reynolds number, *Re*: 5000
Enter the dimensionless roughness size, ε (mm 0.045
Enter the diameter, *D* (mm): 101.6

OUTPUT

Relative Roughness, ε/D = 0.000442913
Result from Colebrook equation (Moody chart): *f* = 0.03788

Fig.2: Interface of Computerized Moody Chart Solver as uploaded on https://www.drkarnteaching.com/

Where ΔP is the pressure drop in a pipe, ρ is the density of the fluid, ε is the roughness height of pipe, f is friction factor, L is the length of pipe, D is the diameter of the pipe and Q denotes the flow rate in a pipe. Pump power can be calculated by the given equation:

$$Power, \dot{W} = Q * \Delta P$$

Finally, the head loss can be calculated by the given equation:

$$Head\ loss, h_L = \frac{\Delta P}{\rho g}$$

Figure 4 demonstrates a flowchart depicting the typical algorithm behind the iterative solution of the Type-IV pipe problem. As the figure shows, the strategy begins with seeking the inputs from the user such as ΔP, L and Q, as well as the fluid properties and the roughness height. However, any solution for the pipe diameter from the Darcy-Weisbach equation can't proceed further without the friction factor. Paradoxically however, friction factor itself depends upon Re and relative roughness height, both of which depend upon the pipe diameter, Hence, the solution must proceed through an iterative scheme, commencing with the judicious selection of a pipe diameter. Theoretically speaking, the selection of a pipe diameter should suffice in enabling us to compute a value of the friction factor, if an explicit equation of friction factor were resorted to. However, to solve the implicit Colebrook equation, another set of repetitive and circular calculations for friction factor must be done. Hence, the calculation must proceed by the assumption of a suitable friction factor so that the LHS and RHS of the implicit Colebrook equation are determined and their difference, δ (say, >0) is determined and concatenated with an array ϕ, which is initially a single-element vector containing a positive quantity (say, x). During the first iteration, the product of α= ϕ(2) ϕ(1) amounts to δx, which is a positive quantity. And hence, the iterations must continue with incremental changes in f till a non-positive value of α is attained. Whenever this sign inversion of α occurs, it is tantamount to saying that the curve intersects the abscissa and a root is obtained, or the most accurate solution of the implicit Colebrook equation is attained. Next, inserting this obtained value of f and other known parameters in the Darcy-Weisbach law, a new value of pipe diameter, D^' can be calculated. The difference between the initially selected diameter and the calculated diameter, δ^' (again, >0) is stored inside another array ψ and the product of the last two elements of this array may be termed as β. The sign-inversion of β is a measure again of the accurate value of pipe diameter that satisfies all the given parameters.

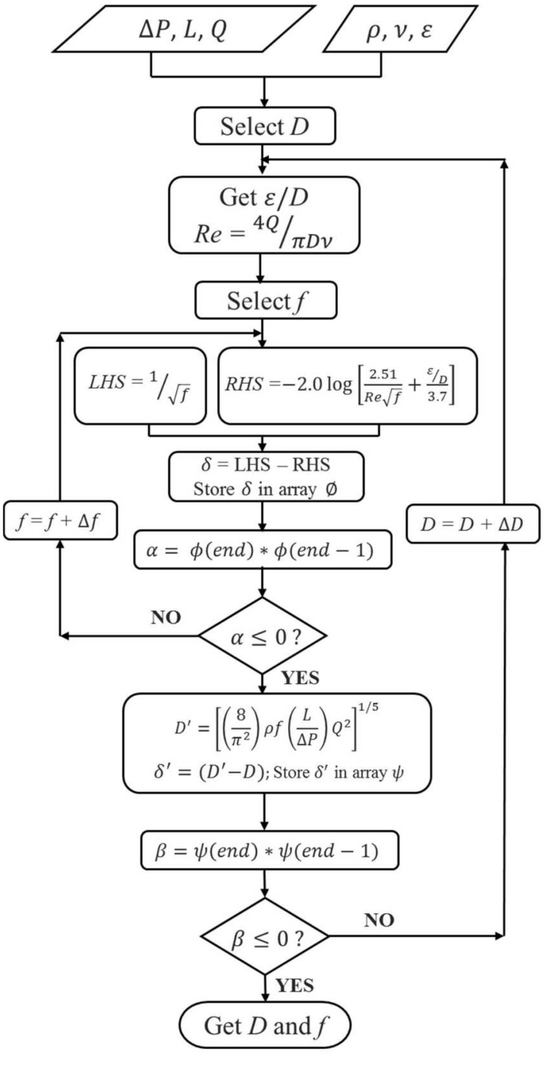
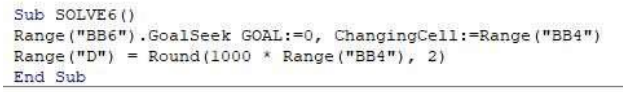


Fig. 4 : Flowchart showing the algorithm behind computation of Type-IV pipe-flow problem. Note that



```
Sub SOLVE6()
Range("BB6").GoalSeek GOAL:=0, ChangingCell:=Range("BB4")
Range("D") = Round(1000 * Range("BB4"), 2)
End Sub
```

Fig. 5 : VBA code showing goal seek method

Although the algorithm of this repeated iterative procedure may look somewhat involved, its actual implementation within the MS-Excel/VBA is rather quite straightforward and simple. In fact, its extremely user-friendly front graphical interface with a very simplistic backend coding in Visual Basic is one of those distinguishing features that makes it truly unique and attractive for developing applications that are easy to develop and use. Actually, this iterative and tedious computation can be very easily carried out in MS Excel with its 'GoalSeek feature'.

The Goal-Seek feature of MS Excel works on the principle of making a target cell reach an assigned value by the variation of a selected other parameter, which is pre-assigned. For instance, in this Type-IV pipe-flow problem, the cell 'BB4' corresponds to the pipe diameter, whereas the cell 'BB6' is the target cell which pertains to the difference between LHS and RHS of the Colebrook equation, which is expected to reach a minimum value (close to zero), whereby the solution to this problem is said to be attained. Figure 5 indeed shows how the intricate algorithm can neatly and elegantly be expressed in few lines using the Goal-seek feature of MS-Excel.

Below, we produce four solved examples of the pipe flow problems of all four types for illustration, and to demonstrate the working and efficacy of the proposed computational tool.

4. Solution Of Some Selected Problems

A. TYPE-I: Given L, Q, D - Calculate ΔP

The following data is given for a pipe flow system as in Example 8.5 from Fox and McDonald's Introduction to Fluid Mechanics, page 372 (Pritchard and Mitchell, 2016):

A 100 m length of smooth horizontal pipe is attached to a large reservoir. A pump is attached to the end of the pipe to pump water into the reservoir at a volume flow rate 0.01 m3/s. What pressure (gage) must the pump produce at the pipe to generate this flow rate? The inside diameter of the smooth pipe is 75 mm.

Here, the user can calculate the pressure drop, knowing the other three parameters (length, diameter, and flow rate). ΔP is calculated using the goal seek method in cell no BB4. Head loss has been calculated using the ΔP value as shown in the given formula in Cell no J23.

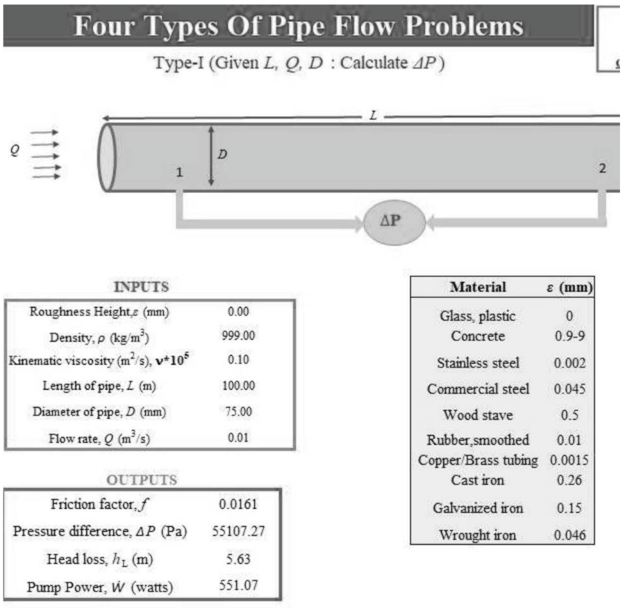
J23 = ROUND(del_P/(rho*9.8),2)

where cell no J23 refers to the value of the head loss. The power of the pump has been calculated using the given formula in cell no J24

J24 = ROUND(Q*del_P,2)

where Cell no J24 refers to the pump power value.

Alternatively, friction factor can also be calculated using the computerized moody chart which can be used to calculate ΔP. As Figure 6 shows, the values given in the problem, length=100 m, flow rate = 0.01 m3/s, diameter = 0.075 m (75 mm) are put in INPUT section of the tool, and it results in a friction factor value of 0.0161, pressure drop in the pipe as 55.11 kPa, a corresponding head loss of 5.63 m and the required pump power to be 551.07 watts. In reality, taking the mechanical efficiency of the pump into account, the pump power required may be slightly larger.



Four Types Of Pipe Flow Problems

Type-I (Given L, Q, D : Calculate ΔP)

INPUTS

Roughness Height, ε (mm)	0.00
Density, ρ (kg/m^3)	999.00
Kinematic viscosity (m^2/s), ν*10^5	0.10
Length of pipe, L (m)	100.00
Diameter of pipe, D (mm)	75.00
Flow rate, Q (m^3/s)	0.01

OUTPUTS

Friction factor, f	0.0161
Pressure difference, ΔP (Pa)	55107.27
Head loss, h_L (m)	5.63
Pump Power, $\dot{W}$ (watts)	551.07

Material	ε (mm)
Glass, plastic	0
Concrete	0.9-9
Stainless steel	0.002
Commercial steel	0.045
Wood stave	0.5
Rubber,smoothed	0.01
Copper/Brass tubing	0.0015
Cast iron	0.26
Galvanized iron	0.15
Wrought iron	0.046

Fig 6 : The solution to the Type-I flow problem from Fox and Mcdonald's Introduction to Fluid Mechanics, page 372 () using the developed computational tool.

B. TYPE-II: Given ΔP, Q, D - Calculate L

The following data is given for a pipe flow system as in Example 8.6 from Fox and McDonald's Introduction to Fluid Mechanics, page 373 (Pritchard and Mitchell, 2016):

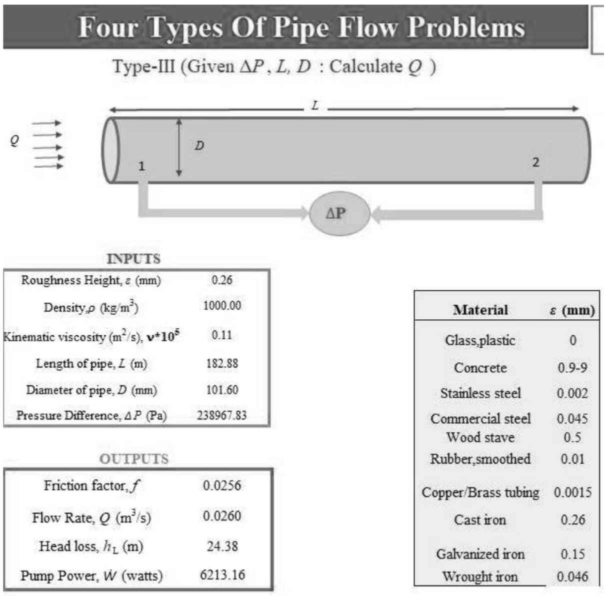
Crude oil flows through a level section of the Alaskan pipeline at a rate of 1.6 million barrels per day (1 barrel=42 gal). The pipe inside diameter is 48 in; it's roughness is equivalent to galvanized iron. The maximum allowable pressure is 1200 psi; the minimum pressure required to keep dissolved gases in solution in the crude oil is 50 psi. The crude oil has SG=0.93; its viscosity at the pumping temperature of 140°F is μ=3.5x10-4 lbf.s/ft2. For these conditions, determine the maximum possible spacing between pumping stations. If the pump efficiency is 85 percent, determine the power that must be supplied at each pumping station.

Here the user can calculate the Length of the pipe knowing the other three parameters (pressure drop, diameter and flow rate). Length of the pipe is calculated using the goal seek method in cell no BB4. Head loss and the required pump power has been calculated as described before in the first sample problem. Friction factor can also be calculated using the computerized moody chart which can be used to calculate L. As figure 7 shows, the values given in the problem, flow rate = 1.6 x 106 barrels per day (2.94 m3/s), diameter=48 inches (1.2192 m or 1219.20 mm), pressure difference = 1150 psi (7928970.89 Pa), density=929.85 kg/m3 are put in INPUT section of tool which results in friction factor value of 0.0170, length of the pipe as 192435.17 m, a corresponding head loss of 870.12 m and the required pump power to be 23344548.76 watts. In reality, considering the mechanical efficiency of the pump, the pump power required may be slightly larger.

C. TYPE-III: Given ΔP, L, D - Calculate Q

The following data is given for a pipe flow system as in Example 8.7 from Fox and Mcdonald's Introduction to Fluid Mechanics, page 375 (Pritchard and Mitchell, 2016):

A fire protection system is supplied from a water tower and standpipe 80 ft tall. The longest pipe in the system is 600 ft and is made of cast iron 20 years old. The pipe contains one gate valve; other minor losses may be neglected. The pipe diameter is 4 in. Determine the maximum rate of flow (gpm) through this pipe.



Four Types Of Pipe Flow Problems

Type-III (Given ΔP, L, D : Calculate Q)

INPUTS

Roughness Height, ε (mm)	0.26
Density, ρ (kg/m^3)	1000.00
Kinematic viscosity (m^2/s), $\nu * 10^5$	0.11
Length of pipe, L (m)	182.88
Diameter of pipe, D (mm)	101.60
Pressure Difference, ΔP (Pa)	238967.83

OUTPUTS

Friction factor, f	0.0256
Flow Rate, Q (m^3/s)	0.0260
Head loss, h_L (m)	24.38
Pump Power, $\dot{W}$ (watts)	6213.16

Material	ε (mm)
Glass,plastic	0
Concrete	0.9-9
Stainless steel	0.002
Commercial steel	0.045
Wood stave	0.5
Rubber,smoothed	0.01
Copper/Brass tubing	0.0015
Cast iron	0.26
Galvanized iron	0.15
Wrought iron	0.046

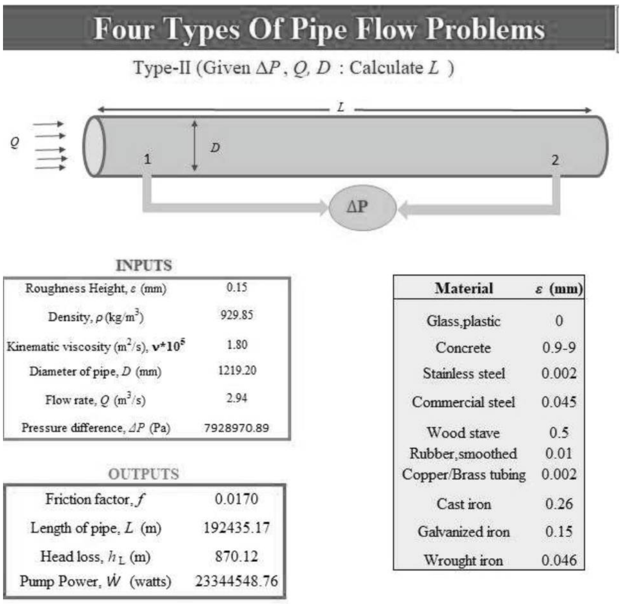
Fig 8: The solution to the Type-III flow problem from Fox and Mcdonald's Introduction to Fluid Mechanics, page 375 () using the developed computational tool.

Here the user can calculate the Flow rate knowing the other three parameters (pressure drop, diameter and length of the pipe). Flow rate is calculated using the goal seek method in cell no BB4. Head loss and the required pump power has been calculated as described before in the first sample problem. As figure 8 shows, the values given in the problem, length=600 ft (182.88 m), diameter = 4 inches (0.1016 m or 101.60 mm), pressure difference of 238967.83 Pa are put in INPUT section of tool which results in friction factor value of 0.0256, flow rate in pipe as 0.0260 m3/s, a corresponding head loss value of 24.38 m and the required pump power to be 6213.16 watts.

D. TYPE-IV: Given ΔP, L, Q - Calculate D

The following data is given for a pipe flow system as in Example 8.8 from Fox and Mcdonald's Introduction to Fluid Mechanics, page 376 (Pritchard and Mitchell, 2016):

Spray heads in an agricultural spraying system are to be supplied with water through 500 ft of drawn



Four Types Of Pipe Flow Problems

Type-II (Given ΔP, Q, D : Calculate L)

INPUTS

Roughness Height, ε (mm)	0.15
Density, ρ (kg/m^3)	929.85
Kinematic viscosity (m^2/s), $\nu * 10^5$	1.80
Diameter of pipe, D (mm)	1219.20
Flow rate, Q (m^3/s)	2.94
Pressure difference, ΔP (Pa)	7928970.89

OUTPUTS

Friction factor, f	0.0170
Length of pipe, L (m)	192435.17
Head loss, h_L (m)	870.12
Pump Power, $\dot{W}$ (watts)	23344548.76

Material	ε (mm)
Glass,plastic	0
Concrete	0.9-9
Stainless steel	0.002
Commercial steel	0.045
Wood stave	0.5
Rubber,smoothed	0.01
Copper/Brass tubing	0.002
Cast iron	0.26
Galvanized iron	0.15
Wrought iron	0.046

Fig. 7 : The solution to the Type-II flow problem from Fox and Mcdonald's Introduction to Fluid Mechanics, page 373 (Pritchard and Mitchell, 2016) using the developed computational tool.

aluminium tubing from an engine driven pump. In its most efficient operating range, the pump output is 1500 gpm at a discharge pressure not exceeding 65psig. For satisfactory operation, the sprinklers must operate at 30 psig or higher pressure. Minor losses and elevation changes may be neglected. Determine the smallest standard pipe size that can be used.

Here the user can calculate the diameter of the pipe knowing the other three parameters (pressure drop, flow rate and length of the pipe). Diameter of the pipe is calculated using the goal seek method in cell no BB4. Head loss and the required pump power has been calculated as described before in the first sample problem. As figure 9 shows, the values given in the problem, length=500 ft (152.40 m), flow rate=1500 gpm (0.09 m3/s), pressure difference = 35 psig (241316.51 Pa) are put in INPUT section of tool which results in friction factor value of 0.0124, diameter of pipe as 0.14161 m (141.61 mm), a corresponding head loss of 24.62 m and the required pump power to be 22837.06 watts.

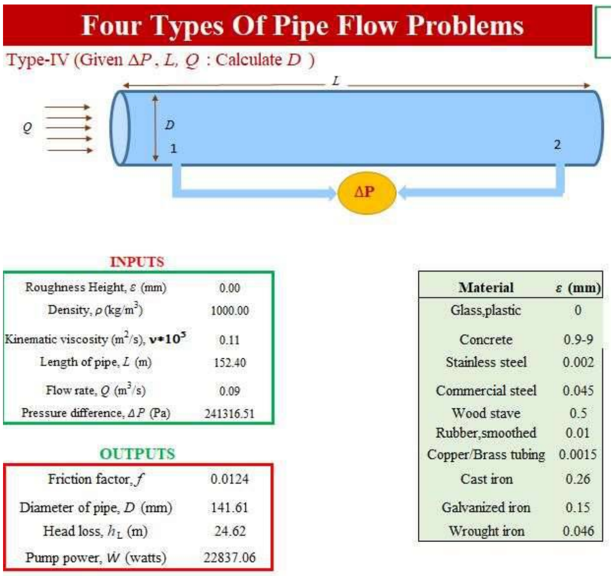
5. Users Surveys And Hypothesis Testing

Finally, to test the efficacy of the developed computational tool in enhancing the teaching and learning of pipe flow problems in undergraduate Fluid mechanics course has been tested by taking sample surveys of a variety of users and the resulting data has been analysed using hypothesis testing principles, to arrive at some substantive conclusions. In order to collect the data, the developed tool was uploaded on the course website https://www.drkarnteaching.com/fluid-mechanics-tools or a blind review and it was given access to the second year B.Tech Mechanical Engineering, Mechatronics Engineering and Automotive Design Engineering students who have studied the Fluid Mechanics course. The tool was also open for review from the B.Tech third year students as well as the faculty/ research scholars who wished to provide the data and feedback for the innovative tool.

The feedback/ data collection form comprised of ten questions, and the users were expected to provide ratings for each of these questions from 1 to 5. In the quantitative part, 1 referred to a strong disagreement whereas 5 indicated the vice-versa, i.e. a strong endorsement. In addition, qualitative feedback was also sought from the participants regarding the different aspects of the computational tools as well as its overall usefulness and effectiveness. Table 1 enlists the ten questions the users of the tool were asked to respond to, apart from their qualitative remarks. A general description of the questions posed in the survey can thus be made: the first questions seeks the user input regarding the overall usefulness of this tool

Table 1 : Statement Of Survey Questions Given to the Users/ Different Alternative Hypotheses In Hypothesis Testing

#	Hypothesis
1.	The developed computational tool considerably improves the overall teaching-learning experience of pipe flows.
2.	This computational design tool inspires students to do quality work.
3.	The developed computational tool helps retain the interest and attention of the students in the Fluid mechanics subject.
4.	The strategy of employing computational tool helps in cooperative peer learning.
5.	The difficulty level of the subject was considerably reduced with the help of this computational solver
6.	This teaching strategy will help students to see integration of computers in engineering education.
7.	This computational solver helps students significantly in applying theoretical concepts to real-life problems.
8.	The Pipe flow interactive tool is a great lecture demonstration to aid students' understanding.
9.	The developed computational tool is helpful in honing problem solving skills during the tutorial sessions.
10.	Based on the benefits derived from this solver, such a computational tool is recommended for other courses.



INPUTS

Roughness Height, ε (mm)	0.00
Density, ρ (kg/m^3)	1000.00
Kinematic viscosity (m^2/s), $\nu*10^5$	0.11
Length of pipe, L (m)	152.40
Flow rate, Q (m^3/s)	0.09
Pressure difference, ΔP (Pa)	241316.51

OUTPUTS

Friction factor, f	0.0124
Diameter of pipe, D (mm)	141.61
Head loss, h_L (m)	24.62
Pump power, $\dot{W}$ (watts)	22837.06

Material	ε (mm)
Glass,plastic	0
Concrete	0.9-9
Stainless steel	0.002
Commercial steel	0.045
Wood stave	0.5
Rubber,smoothed	0.01
Copper/Brass tubing	0.0015
Cast iron	0.26
Galvanized iron	0.15
Wrought iron	0.046

Fig. 9 : The solution to the Type-IV flow problem from Fox and Mcdonald's Introduction to Fluid Mechanics, page 376 (Pritchard and Mitchell, 2016) using the developed computational tool.

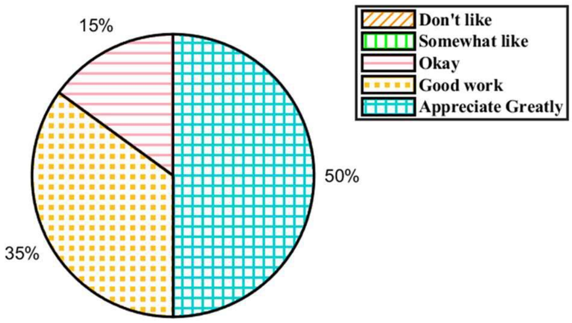


Fig. 10 : User perceptions on overall improvement of the teaching-learning experience of pipe flows.

in teaching and learning of pipe flows, whereas the last query specifically pertains to whether based on the benefit derived from such tools in the Fluid mechanics course, the students would like to see such a strategy being implemented in other engineering courses. The middle eight questions are further grouped under two heads: the first one relates specifically to the students' perceptions regarding aiding self-learning (question # 2-5) and includes difficulty reduction, creating opportunities for cooperative learning, sustaining their interest in the subject as well as assistance that such tools provide in doing quality work in engineering. The second group pertains to the instructor and instructional perspective, such as enabling students to see the computers in engineering professions, enabling students to teach real-life problems, facilitating lecture demonstration of crucial concepts, as well as aiding in the smooth conduction of tutorial sessions for the students. A total of twenty user responses were received. These users belonged to the different states of India.

A. Overall acceptance of new method

Figure 10 displays a pie chart of the user perceptions regarding the overall acceptance of the developed computational tool in enhancing teaching-learning experience in pipe flows. While analysing the user inputs, the entries on a numeric scale of one to five has been interpreted as 'Don't like', 'Somewhat like', 'Okay', 'Good work' and 'Appreciate greatly', respectively. As per this adaptation, the figure shows that about 50% of the users provide a greatly positive endorsement for this tool, while another 35% of the population applaud this work. The rest 15% of the population affirm the new computational tool to be 'okay' in its usefulness and none of the users provided a lesser rating for the developed innovative tool, which validates our claim regarding the overall usefulness of the tool.

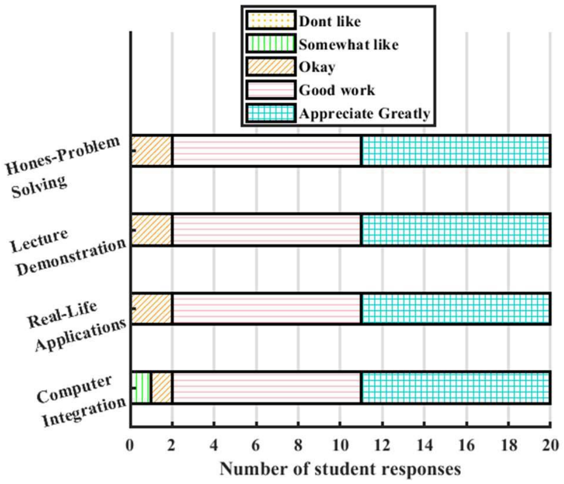


Fig. 12 : Students' perceptions regarding the role of pipe flows computational tools in promoting instructional aspects of the course.

B. User perceptions on aiding Self-learning

Figure 11 displays a bar plot of the students' perceptions regarding the role of computational tool in aiding self-learning of the concepts related to hydraulic losses and engineering design of pipe systems for fluid flow application. As the figure shows, under all the different segments such as the role of the tool in reducing the difficulty of the pipe flow concepts, promotion of cooperative learning, its usefulness in sustaining the interest of the students in the learning of fluid mechanics and pipe flows, as well as facilitating quality improvement of the course delivery, about 12 users have greatly appreciated this initiative, while another 6 users have applauded the initiative as a 'commendable work'. There was no user who opted for the 'Don't like' option under any of the divisions under this group. This makes the cardinal role of these computational tools in assisting self-learning of students, amply clear.

C. User perceptions on Instructional aspects

The response of the users from another standpoint of improvement in the instructional aspects of the course delivery has then been examined. Figure 12 again shows that an an enormous majority (nine users under each) of the user population has commended the usage of the developed computational tools on friction factor and hydraulic losses in pipe flows by providing the highest and the next highest rating, respectively.

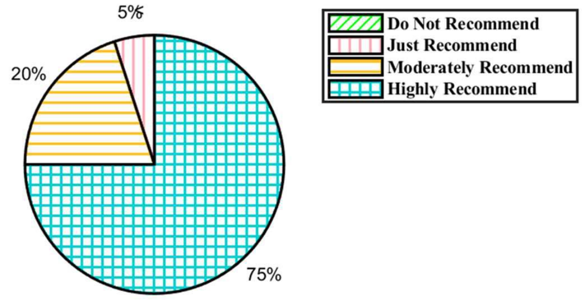


Fig.13:User responses regarding their recommendation of introduction of such tools in other engineering courses.

There was hardly one user who 'somewhat liked' the usage of computational tools as far as the integration of computers in engineering professions is concerned. This is not surprising since the adoption of a completely novel pedagogy to engineering problem-solving through sophisticated tools may put some in a state of discomfiture, particularly if they are not comfortable with computers. This is expected since some students show a marked preference to 'pen-and-paper' and 'pattern-recognition' approach to problem solving. However, even this student seem to have appreciated the role of the proposed innovation in imparting real-life engineering skills, its importance in honing problem-solving skills during tutorial sessions and that it can be befittingly used as an excellent lecture demonstration to aid student learning. Overall, the data testifies to the effectiveness of the developed tools in enhancing instructional aspects of the course delivery.

D. Recommendation for Other Courses

Finally, it would be worth knowing the opinions of the users regarding the recommendation of such a pedagogy to other engineering domains. This may be important to know before we can generalize the observations procured from a single Fluid mechanics course, and may extrapolate it to the other courses in Mechanical engineering such as Strength of Materials or Manufacturing technology. However, unlike other questions, while answering this question, the users were provided with only four options: 'Don't recommend', 'Just recommend', 'Moderately recommend' and 'Highly recommend'. Figure 13 evinces the quantitative evidence of the user responses. As it shows, the user responses lie within the top three affirmative categories only, with 75%, 20% and 5% responses, respectively. This clearly explicates the notion of the engineering users that such a pedagogy must be introduced in other engineering courses as well.

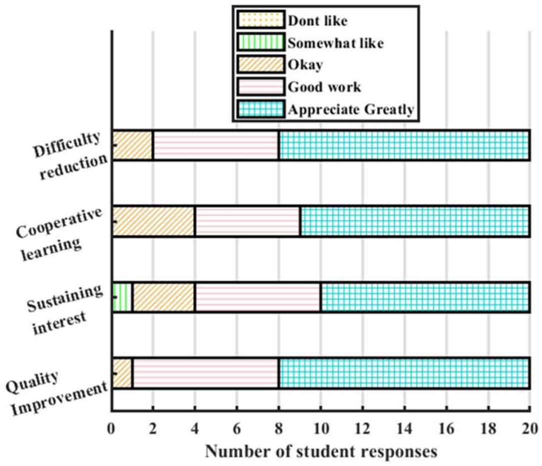


Fig. 11 : Students' perceptions regarding the role of pipe flows computational tools aiding self-learning.

E. Analysis of the Hypothesis testing results

Hypothesis testing is a way to find out whether a hypothesis in respect to a population can be considered acceptable. A hypothesis is basically a presumption about something. The actual test begins by considering two hypotheses: the null hypothesis (H0) and the alternative hypothesis (Ha). The alternative hypothesis is a claim about the population that is contradictory to H0 and what is naturally concluded upon rejection of H0. Since the null and alternative hypotheses are contradictory, one must examine evidence to decide if there exists enough evidence to reject the null hypothesis or not. The evidence is in the form of sample data. After it has been determined which hypothesis the sample supports, two possible decisions could be made: "reject H0" if the sample information favours the alternative hypothesis or "decline to reject H0" if the sample information is insufficient to reject the null hypothesis. For instance, the first hypothesis (of the ten hypotheses presented in this manuscript) as presented in Table 1 can be written technically as follows:

H0: The developed computational tool does not considerably improve the overall teaching-learning experience of pipe flows.

Ha: The developed computational tool considerably improves the overall teaching-learning experience of pipe flows.

On the basis of population and type of data, there are many tests that can be used for hypothesis testing.

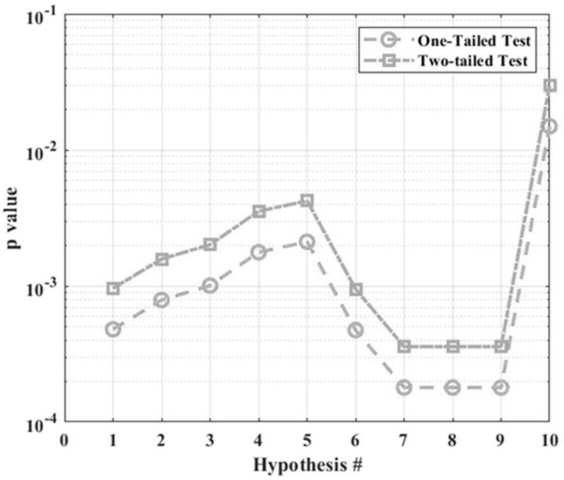


Fig. 14 : p values for all hypotheses presented in Table 1, using 'One-Tailed t-test' and 'Two-tailed t-test'.

Out of all these several tests, the “t-test” is considered most suitable for the present population, and thus we have conducted both ‘One-Tailed test’ and ‘Two-tailed t-test’ to calculate the p value, which in statistics is the probability of obtaining results at least as extreme as the observed results of a hypothesis test, assuming null hypothesis to be correct. Thus, a smaller p value (< 0.05) implies that the alternate hypothesis is correct. The “t-test” feature is in-built in Excel under the Data analysis tool pack section in which variable range can be selected and it gives the output of mean, number of observations, variance and p value for ‘One-tailed t-test’ and ‘Two-tailed t-test’.

Figure 14 presents the p values for all the hypotheses presented in Table 1. As the figure shows, there is a slight variation between the p values of different hypotheses, but the trends of variation of One-Tailed test and Two-tailed test remain the same. Further, the upper bound of these p-values are 0.002 and 0.0044, and since p value is lesser than 0.05 for all the hypotheses, these represent statistically significant test result, i.e. the null hypothesis is false and must be rejected for all the statements presented in Table 1. Thus, the results of hypothesis testing clearly and definitely substantiates the usage of these computational tools in the fluids education in particular, and to some extent, engineering education in general. It is expected that the development of such computational tools may open a new foray into which concerted development of engineering pedagogy could take place, and which has a potential of transforming both engineering education in terms of delivery and self-learning.

6. Conclusion

The approach developed in this paper for solving four types of pipe flow problems provides a reliable, efficient means of explicitly determining a variety of design parameters for pipe flow problems. Manual solutions to these types of problems requires time and is a difficult process as it involves iterative calculations. This approach also provides an efficient technique to enhance real-time modelling, which requires the reliable, fast calculation of many of the parameters discussed in this paper. The paper demonstrates the use of spreadsheets as an educational tool in the area of analysis of hydraulic losses in pipes. In addition to helping the student understand the concepts of analysis and design, it clarifies the concepts behind solving the set of governing equations. Certain features like Goal-seek method inherent to spreadsheets were used to perform the iterative calculations needed for the friction factor and the ‘macros’ feature of MS-Excel was used to automate the solution. Spreadsheets are invaluable for the instructor also since it helps him design better assignments and test problems. Other platforms were also available for designing of computational tool, but MS Excel provides the maximum ease in designing such tools and is more student-friendly due to its inherent simplicity. User surveys were also conducted to find out whether this design helps students and instructors in effective ways. Detailed reviews were taken from the users on eight different aspects and the user responses were found overwhelmingly positive on all the fronts – both from the viewpoints of improvement in instructional aspects of the course as well as its effectiveness in aiding self-learning for students. Using the data gathered from the users, a hypothesis testing was done to validate the ten hypothesis statements, and a p value lower than 0.05 for all the hypotheses allows us to conclude that the proposed computational tools are found to be extremely effective both for teaching and learning purposes. In addition, the users strongly recommend such interventions in other engineering courses. To sum it up, the current manuscript does not only report the design of relevant computational tools for the teaching and learning of pipe flows in the undergraduate fluid mechanics curriculum, but also presents the detailed methodology that can provide enough cues to one who wishes to design such computational tools. The developed computational tool has been provided on a self-created open-source website (drkarnteaching.com/) freely to be used by the students and engineering instructors alike.

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