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DESIGN OF PUMPING INSTALLATIONS: DEVELOPMENT OF AN EXCEL WORKBOOK FOR HYDRAULIC MACHINES LECTURES

A. Virgílio M. Oliveira[1,3]*, Javier Ruiz Ramírez[2] and João Ferreira Mendes[1]

1: Polytechnic Institute of Coimbra, Coimbra Institute of Engineering, Rua Pedro Nunes - Quinta da Nora, 3030-199 Coimbra, Portugal.
e-mail: avfmo@isec.pt
2: Departamento de Ingeniería Mecánica y Energía, Universidad Miguel Hernández de Elche, Avda. Universidad s/n, Edificio Innova, 03202 Elche.
3: ADAI, Department of Mechanical Engineering, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal

Abstract: *Nowadays, pumps are used worldwide in a very wide range of facilities and for countless purposes, including HVAC, domestic and commercial buildings, district energy, industrial processes and water treatment, municipal wastewater and water supply, agriculture and irrigation, among others. The objective of the present contribution is to introduce an Excel Workbook that presents a friendly easy to use tool that enables the design of pumping systems with centrifugal pumps. It was first thought for Hydraulic Machines Master lectures, but its use might be looked at in a wider perspective. The Workbook includes 17 worksheets (Figure 1), all linked to each other, addressing different aspects of the design. Special attention is paid to the major and minor head losses calculation, the cavitation phenomenon, the use of dimensionless coefficients to determine the rotation speed to obtain a specific operating point, and to the calculation of the system curve. Energy efficiency represents today an important goal in every pumping facility; therefore, one of the objectives of this tool is to enable the user to quantify both the shaft power and the efficiency of different operating points thus allowing a definition of the best solution.*

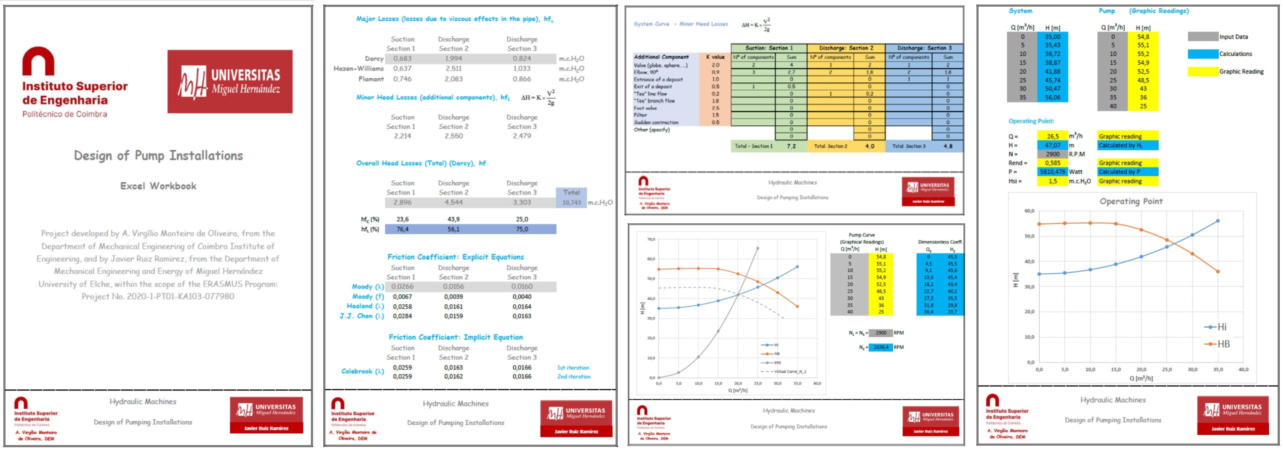

Figure 1: View of some worksheets.

Keywords: Hydraulic Machines, Centrifugal Pumps, Performance curves, Dimensionless coefficients, Electronic-speed controllers.

1. INTRODUCTION

Energy efficiency is a top priority topic in the current times, not only in the domain of engineering but also beyond. This importance may even escalate significantly in the future, particularly as energy demand is expected to increase. The design of energy efficient systems can be compared to an international competition race, in which the winner will be better prepared to face the future. Under this perspective, pumping systems will be looked at as a field where energy efficiency will play a role as important as the intrinsic goal of the pump itself plays actually. The design and pursuit of energy efficient pumps represent already of the main goals, if not the main goal, of pump manufacturers.

Nowadays, pumps are used worldwide in a very wide range of facilities, including refrigeration, air-conditioning, boilers, water supply, aquaculture, … One might argue that it is impossible to count the number of pumps working today, or even to have a rough estimation. Accordingly, it is also impossible to have an idea of the power demand that pumps are requiring today; perhaps even more difficult, is to be aware of typical efficiency values! Across the life-cycle of a pump, the overall costs include the purchase, the maintenance (i.e. replacement of mechanical shaft seals, of electric motors, of impellers, …), the daily energy expenditures and also other possible expenses. The contribution of the energy costs in the whole-life of a pump can be very significant. Different reference values for these costs can be found in the literature, in some cases reaching up to 40%. Therefore, the daily operation of a pump represents a very important issue.

The present contribution addresses these objectives by proposing an Excel workbook, entitled “EEP: **E**nergy **E**fficient **P**umps Design Tool”, designed to the achievement of energy efficient pumping systems. The development of applications similar to this one should not be looked at as a tool useful to the academic community; on the contrary, the main goal is directed to real-world applicability and to the design of more energy efficient pumping systems. However, and at the same time, it may also represent a bridge between a theoretical approach, since some fundamental issues are addressed, and a practical easy-to-use tool in the everyday life of an engineer. Therefore, this Excel Workbook makes available a friendly tool that enables the analysis and design of pumping systems. Since centrifugal pumps are widely used and most probably represent the most common type of pumps worldwide, the Workbook was developed by considering that type of pumps. Pump manufacturers like Grundfos (www.grundfos.com), have available online software that represents the state-of-the-art in this field and that enables users to select and to design of pumping systems.

This study represents one outcome of an ongoing cooperation between Miguel Hernández University (UMH) of Elche, in Spain, and Coimbra Institute of Engineering (ISEC), in Portugal; it was started in April 2023 (from 3 to 6th) under the ERAMUS + program, and was further developed in June (from 5 to 9th) and also in the period between November 27th and December 1st. Moreover, in the current academic year (2023-2024), a Master supervision of a Portuguese student is also being shared, involving the three authors. The present application was first thought for Hydraulic Machines Master Lectures, but throughout its development it was enhanced to answer to a more a wider perspective. In some contexts, it might be a useful tool for engineers involved in the design of pumping systems.

2. ORGANIZATION OF THE WORRKBOOK

The first question to be answered in the design of a pumping installation, is to know what type of pump is required. Grundfos (www.grundfos.com), one of the main manufacturers of pumps worldwide, has several technical alternatives available, namely, circulator, booster set, inline single stage, endsuction close coupled single stage, endsuction long coupled single stage, horizontal split case, endsuction close coupled multistage, inline multistage, horizontal multistage, immersible, endsuction machine tool, encapsulated, submersible wastewater, submersible groundwater, and diaphragm pumps. Upon selection of the type of pump required for the installation under analysis, the user must have available the technical catalogue/datasheets of the models available for that type of pump. Usually, the manufactures have available a selection diagram, where all the models, each with a specific commercial code, and range both in terms of flowrate and head rise are shown. To start working with the Excel workbook, this data must be available.

The workbook comprises 17 worksheets; the first ones are just introductory (front page, nomenclature and main formulas) followed by the “Pump curve”, “Material”, “Coef._K”, “System curve”, “Material_Flamant”, “Material_Hazen-Williams”, “Head losses”, “Pump selection”, “Operating point”, “PPE & point 3”, “Point 2”, “Cavitation”, “Table 3 points” and “Units”; this the last worksheet allows the user to convert some of the most used units in this field. The workbook is almost entirely protected, which means that no changes in most cells are allowed; only the cells that require input data were left unprotected. This way, unintentional changes in the cells with formulas, with specific values, with values based on calculations or data from other worksheets are not permitted. Furthermore, the workbook should be looked at as an open tool, and several improvements might be considered, depending on the specific goals of the user. For the present purposes, the main objective was firstly directed to the lectures of Hydraulic Machines of Mechanical Engineering Degree of ISEC. It was further developed following the third ERAMUS mobility, between November 27th and December 1st of 2023, in order to meet specific objectives of Fluid Installations Lectures of the Master in HVAC and Electrical Facilities, Energy Efficiency at UMH.

3. MAJOR HEAD LOSSES, FRICTION COEFFICIENT AND MINOR HEAD LOSSES

A detailed assessment of head losses in a given installation requires thorough analysis and is cumbersome. Therefore, it is neither common nor practical. Several simplifications are thus assumed, namely in typical engineering projects; the assumption that the minor head losses can be estimated on the basis of a given percentage of the total length of the installation represents a good example of this approach. The concern regarding the accuracy in the calculation of head losses is more related to the academic and the scientific communities rather than among engineers that have to deal with projects on a daily-basis, with deadlines always too short to accomplish. Nevertheless, as stated by Coelho et al (2018), in a study dedicated to irrigation engineering projects, the calculation of head losses is the most important factor to take into account. Accordingly, in the design of pumping systems, despite the low viscosity of the water and its very low compressibility, the head losses might assume a very significant value and thus have a clear influence on the operating point. Therefore, in the present workbook, a special attention is given to this issue.

A very significant number of equations are available in the literature to estimate the head losses. The head losses depend on various factors, namely the temperature and the viscosity of the fluid, the material, diameter and length of the pipe, and the flow velocity. The equations to estimate the head losses are determined according to the specific flow regime, Laminar or Turbulent, which is defined on the basis of the Reynolds number (Re); Re represents the relation between the inertial and the viscous forces and is calculated as follows:

$$Re = \frac{\rho \times V \times L^*}{\mu} = \frac{V \times L^*}{\upsilon} \qquad (1)$$

where: Re – Reynolds number (adm), ρ - Density [kg/m^3], V – Mean velocity of the fluid in a pipe [m/s], L^* - Characteristic dimension [m], μ - Dynamic viscosity [N.s/m^2] and ν - Kinematic viscosity [m^2/s].

The characteristic dimension (L*) corresponds, in the case of flows in circular pipes, to the internal diameter of the pipe; also in circular pipes, if $Re < 2000$, the flow is assumed as Laminar; if $Re > 4000$ the flow is Turbulent and the region between $2000 < Re < 4000$ is considered as a transition zone, in which both inertial and viscous forces may prevail. For the present purposes, and since in pumping systems the flow is "almost" always turbulent, this is the only flow regime considered for the head losses calculations. However, if for any reason the Reynolds number is below 2000, this is highlighted in the workbook as an alert and the corresponding cell appears red together with the word "Laminar" also in red text. Otherwise, if Re is between 2000 and 4000 the word "Transition" will be shown.

In the present workbook, both major and minor head losses are considered. Among the large number of equations available to estimate the friction losses, the ones proposed by Darcy-Weisbach, by Hazen-Williams and by Flamant were selected; on the other hand, the friction coefficient is estimated with both explicit (Haaland, J.J. Chen and Moody, which was taken for reference), and implicit (Colebrook, the first iteration is based on the result obtained with the Moody equation) equations (Marques e Sousa, 1997; Sousa et al, 1999).

The Darcy-Weisbach equation, valid for any fully developed, steady, incompressible pipe (placed horizontally or with a slope) flow (Young et al., 2012), is given by:

$$h_f = \left(\frac{\lambda \times L}{d}\right) \times \frac{V^2}{2 \times g} \qquad (2)$$

where: hf – Major head losses [m.c.H_2O], λ - Friction coefficient (Moody] (adm), L - Length of the pipe [m], d - Diameter of the pipe [m], V - Velocity of the fluid in a pipe [m/s] and g - Acceleration of gravity [m/s^2].

The Hazen-Williams equation is given by:

$$h_f = \frac{10{,}643 \times L \times Q^{1{,}85}}{C_{H-W}^{1{,}85} \times d^{4{,}87}} \qquad (3)$$

where: Q - Flowrate [m^3/s] and $C_{H\text{-}W}$ - Hazen-Williams coefficient, adm and the Flamant equation is given by:

$$h_f = 22494 \times L \times C_F \frac{V^{1,75}}{d^{1,25}} \tag{4}$$

where: C_F - Flamant coefficient (adm) and d - Diameter of the pipe [mm].
The explicit equations to calculate the Friction factor are the following:

$$\text{Moody: } \lambda = 0{,}0055 \times \left[1 + \left(20000 \times \frac{\varepsilon}{d} + \frac{10^6}{Re}\right)^{1/3}\right] \tag{5}$$

$$\text{Halland: } \frac{1}{\sqrt{\lambda}} = -1{,}8 \times log\left[\left(\frac{\varepsilon}{3{,}7 \times d}\right)^{1,11} + \frac{6{,}9}{Re}\right] \tag{6}$$

$$\text{J.J. Chen: } \lambda = 0{,}3164 \times \left(0{,}11 \times \frac{\varepsilon}{d} + \frac{1}{Re^{0,83}}\right)^{0,3} \tag{7}$$

where: ε- Roughness of the pipe wall [mm].
The implicit equation to calculate the Friction factor was proposed by Colebrook-White:

$$\frac{1}{\sqrt{\lambda}} = -2 \times log\left[\left(\frac{\varepsilon}{3{,}7 \times d}\right) + \frac{2{,}51}{Re \times \sqrt{\lambda}}\right] \tag{8}$$

The pressure drop (ΔP) in a given component might be obtained in different ways, namely through the flow coefficient (K_v, [(m^3/h)/($bar^{1/2}$)]), an approach mostly used in flow control valves, with the help of graphs usually proposed by manufacturers for their specific components (these two cases usually expressed in pressure units), and also indirectly through the use of the minor head loss coefficient (K_L). This last method is, probably, the most common way to estimate the head loss in a given component. In this case, components head losses or pressure drops are determined by specifying the minor head loss coefficient (K_L) (Young et al, 2012):

$$K_L = \frac{h_f}{\left({V^2}/{2 \times g}\right)} = \frac{\Delta P}{\frac{1}{2} \times \rho \times V^2} \tag{9}$$

Finally, the minor head losses are usually expressed by the following equation:

$$h_f = K_L \times \frac{V^2}{2 \times g} \tag{10}$$

where: K_L – Minor head loss coefficient of a given component, adm

Therefore, the head loss information based on the K_L value is given in a dimensionless form. When K_L is equal to 1, the pressure drop is equal to the dynamic pressure (${1}/{2} \times \rho \times V^2$), and for a given value of K_L the pressure drop is proportional to the square of the velocity. The K_L coefficient is not constant, it actually decreases with the flowrate towards a value approximately constant; therefore, for high Reynolds numbers, the K_L value of a given component depends, essentially, on its geometrical shape (Bistafa, 2010). The minor head loss coefficient K_L is usually obtained experimentally by placing the component in a pipe; for a given flow, the pressure drop between the entrance and exit of the component is measured, thus allowing the estimation of K_L. As for the friction coefficient in the rough area, where a "constant" value is usually assumed, the same procedure is considered for the minor head loss coefficient of a given component (K_L). There is a specific worksheet entitled "Coefi._K" where the user has available the K_L value of the most common components of a hydraulic installation, namely valves (globe, sphere, …), elbows 90º, entrance and exit of deposits, "tee" line and branch flows, foot valves, filters, sudden contractions; in addition, the user can add a specific component, indicating its K_L value. A default K_L value is suggested for each component, but the user can change this option and choose another considered more appropriated; for instance, for a 90º elbow, the default value is 0,9 but the options 0.85; 0.80; 0.75 and 0.70 are also available. For this purpose, Excel drop down lists are available for the different components. For each section of the installation, the user just has to select which and how many components the respective section has; the sum is then performed automatically. Moreover, it is also highlighted that the user might add more components, if necessary. The ones that are defined correspond to the most typical and are thus shown also for guidance.
In the case of the major losses, all the details and calculations are performed and presented in the worksheet entitled "Head Losses". However, in the cases of the Flamant and the Hazen-Williams head losses estimations, the selection of the material is performed in separate worksheets, entitled "Material_Flamant" and "Material_Hazen-Williams", respectively. The user just has to select, for each section of the installation, the right material; the respective coefficients are then automatically considered in the major losses' calculation

("Head Losses" worksheet). All these results are presented in the worksheet entitled "Head Losses". The major head losses estimated by the Darcy-Weisbach equation, and the friction coefficient estimated by the Moody equation, are considered for reference. Finally, the total head losses are estimated by:

$$h_f = \left(\frac{\lambda \times L}{d} + \sum K\right) \times \frac{V^2}{2 \times g} \qquad (11)$$

where: ΣK - sum of the loss coefficients of the additional components ("minor" head losses)

4. SYSTEM CURVE

The System Curve is obtained by:

$$H_i = H_0 + K' \times Q^2 \qquad (12)$$

where Hi - Head rise (system installation) [m], H_0 – Hight coefficient (geometric difference + pressure difference between reservoirs) and K' - Global coefficient of head losses as a function of the flowrate.
The K' coefficient is obtained by: $K' = \frac{8 \times K_T}{\pi^2 \times d^4 \times g}$ (13) and K_T is obtained by: $K_T = \frac{\lambda \times L}{d} + \sum K_L$ (14)
where K_T - Global coefficient of head losses as a function of the fluid velocity.
Despite having available different methodologies to perform the calculation of the system curve, a reference method is proposed. However, by having available in the workbook other options, the user might easily assume different scenarios. Hence, it is important to emphasize that K_T in the default System Curve is obtained on the basis of the friction coefficient λ calculated with the Moody equation, the major losses are calculated with the Darcy-Weisbach equation, and the minor head loss coefficient K_L of each component is based on a fixed value presented in the respective worksheet ("Coef._K").

5. PUMP PERFORMANCE CURVES

Once the equation of the system curve is known, the head rise (or manometric head, H) for the required flowrate can be calculated. This pair of values (H-Q) allows, by consulting the selection diagram of the suitable type of pump, a first selection of a couple of models. The next step consists on the analysis of the performance curves of each of the models selected. For each model, the user must carefully read the information of the pump (characteristic H-Q, efficiency, power and NPSH curves) made graphically available by the manufacturer and then select a few reference points (we recommend at least 10 points) to specify in the respective worksheet ("Pump curve"). This procedure must be done for each curve (H-Q, P, η and NPSH curves). After this step there is no-more need to look at the manufacturer data, as all further analysis is performed within the workbook. To improve accuracy in the graphical reading of the manufacturer data, a special attention is required, as this step will have an influence in all the forgoing analysis and calculations.

6. DIMENSIONLESS COEFFICIENTS

Dimensionless coefficients (DC) might be used for different purposes. In the present context, they are used between operating points that belong to a given parable of equivalent points (PEP). This analysis is necessary to calculate the rotation speed of the pump for a new required operating point, named "Point 2", which represents a new condition of operation, different from the one that is obtained when the pump is firstly placed in the installation (point 1). The PEP determined on the basis of mentioned point 2 is obtained by:

$$H = K \times Q^2 \qquad (15)$$

Hence, every two points that satisfy equation (16) allow the use of DC. For the present analysis, four DC are used, the Flow, the Head Rise, the Power and the Thoma coefficients; they are calculated as follows:

$$\frac{Q}{N \times D^3} \quad (16) \qquad \frac{g \times H}{N^2 \times D^2} \quad (17) \qquad \frac{P}{\rho \times N^3 \times D^5} \quad (18) \qquad \frac{NPSH_{required}}{H} \quad (19)$$

Therefore, typically, three operating points are considered. Point 1 represents the first condition, obtained when the pump is placed in the installation at the reference rotation speed indicated by the manufacturer; point 2 represents the new required condition, at a different rotation speed, to be determined, and point 3 corresponds to the condition obtained in the reference performance curve of the manufacturer, but that belongs to the same PEP determined on the basis of point 2. The PEP and the characteristics of point 3 are determined in worksheet "PEP and point 3" and the conditions of point 2, obtained with DC, are calculated in worksheet "Point 2".

7. NET POSITIVE SUCTION HEAD (NPSH)

The worksheet entitled “Cavitation” is dedicated to the analysis of the cavitation phenomenon. Whenever the Net Positive Suction Head (NPSH) required by the pump, value specified by the manufacturer, is lower than the NPSH available in the installation ($NPSH_{required} < NPSH_{available}$) there is no cavitation. Therefore, these two values are compared in the worksheet. $NPSH_{available}$ is calculated by:

$$NPSH_{available} = \frac{Pa}{\gamma} - e_s - \Delta H_{suction} - \frac{Pv}{\gamma} \qquad (20)$$

where Pa - Atmospheric pressure [Pa], γ - Specific weight [N/m^3], e_s - Height of the pump in the installation [m], $\Delta H_{suction}$ - Head losses in the suction pipe of the pump [m.c.H_2O] and Pv – Fluid vapour pressure [Pa]. For a given condition of operation (points 1, 2 or 3), the atmospheric and the vapour pressures are introduced (Pascal and mm.c.Hg units are permitted) together with the value of e_s, i.e., geometric difference measured vertically between the level of aspiration, assumed for reference, and the pump; all the calculations and the interpretation are then performed in the worksheet.

8. CONCLUSION

The “EEP: **E**nergy **E**fficient **P**umps Design Tool” Excel workbook represents one contribution to be used by project engineers and academic staff whenever a plan of an energy efficient pumping system is foreseen. The workbook includes several features, including a comparison of equations for the estimation of the head losses in pipes (major losses), a comparison of equations for the estimation of the friction coefficient (λ), including explicit and implicit equations, a procedure to obtain the system equation of a given installation, a procedure to calculate the rotation speed of the pump to obtain a specific operating point and a procedure to assess the occurrence of cavitation, among others. Some limitations must obviously be underlined, namely with regard to the calculations of the major head losses (only the Darcy-Weishbach, the Hazen-Williams and the Flamant equations are used), the friction coefficient (estimated with explicit -Haaland, J.J. Chen and Moody-, and implicit -Colebrook- equations), and minor head losses, determined on the basis of the K_L value; it should also be mentioned that the system curve is determined considering one suction section and two discharge sections. Despite these limitations, which are all easily overcome by implementing the necessary changes in Excel, the Workbook allows an overall assessment of a pumping system according to the specific goals of the user.

Finally, the authors would like to emphasize the nature of the present contribution which represents the spirit of ERASMUS within the European Union; upon the first Erasmus Mobility, the goal to design a tool to be used in ISEC-Portugal and UMH-Spain started to come to light. At the present stage of development, the “EEP Design Tool” already meets several of the initial objectives, but its development is still in progress; the enhancement of some of the present features, and the introduction of more interactive and alternative design tools in pumping systems are foreseen. Moreover, hopefully, the authors wish to contribute to the reinforcement of the ongoing cooperation between the two institutions involved.

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