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Numerical Analysis of the Pressure Drop in Industrial Pipes with Non-Uniform Roughness and Helical Ribs in the Case of Laminar Flow

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Abstract—**This study describes a simple and easy-to-implement method to determine the pressure drop in industrial pipes with non-uniform roughness and helical ribs in the case of laminar flow. The effects of the pipe geometrical parameters on the laminar flow regime are discussed. The proposed method of solution and the accuracy of the numerical calculation are shown by the computed results.**

Keywords—industrial pipe; helical ribs; laminar flow; pressure drop

I. Introduction

In the recent years, the scientific research interest in fluid flow and heat transfer with an extensive program of experiments and numerical simulations is focused both on improving the equipment design and on simulation tools and techniques [1-3]. Most of the available literature about the laminar flow in pipes deals with various practical industrial applications offering quantitative data essential for the construction of efficient fluid handling systems [4-7].

A few experimental studies and numerical reports have investigated the roles of surface roughness on the friction characteristics and flow regime behavior in industrial pipes [6-8].

Numerical methods of sophisticated techniques in conjunction with computational power of modern computers have led to the theoretical study of complicated flow situations, to obtain data required for the practical implementation of the results in actual industrial processes [3-5].

In the present study, a numerical analysis has been chosen since it is a more suitable tool to investigate the pressure drop in industrial pipes with non-uniform roughness and helical ribs in the case of laminar flow.

II. Computational Method

A model of a hydraulic pipe with 3 helical ribs has been used (as shown in Figure I, with sections in longitudinal and transverse plane). The hydraulic pipe has a ring-centric section, with geometrical helical ribs, thin and fair shapes. This solution has been chosen in order to simplify the model [6].

The 3D model [9-15] was obtained by parametric modeling with AutoCAD 2017 software [16].

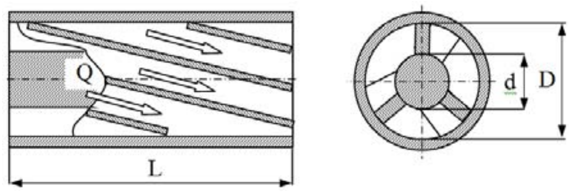


FIGURE I. SCHEMATIC VIEW OF A HYDRAULIC PIPE WITH 3 HELICAL RIBS

Let's consider the following dimensionless values:

$$u = \frac{d}{D}; \qquad w = \frac{L}{D}; \qquad v = \frac{b}{D}; \tag{1}$$

with the next limits of variation:

$$u = [0..1]; \;\; v = [0.01..0.03] \; ; \;\; w > 0; \tag{2}$$

and the coefficients:

$$B = u\sqrt{1 + (\frac{1}{\pi \cdot w})^2} \;\text{ and }\; C = \sqrt{1 + (\frac{u}{\pi \cdot w})^2} \tag{3}$$

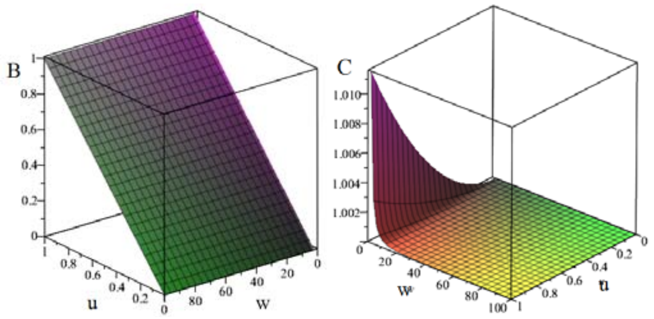
The hydraulic diameter can be calculated using the following formula [6]:

$$D_H = D\frac{(1-u)\left[\frac{2u}{\pi(1-u)}(C-B) - \frac{6v}{\pi}\right]}{\left[\frac{u}{\pi w}\left(\frac{1}{C} + \frac{u}{B}\right) + \frac{3}{\pi}(1-u) - \frac{6v}{\pi}\right]} \tag{4}$$

and can be expressed in an equivalent form:

$$D_H = D\frac{(1-u)\left[\frac{2u}{\pi(1-u)}\left(\sqrt{1+(\frac{u}{\pi\cdot w})^2}-u\sqrt{1+(\frac{1}{\pi\cdot w})^2}\right)-\frac{6v}{\pi}\right]}{\left[\frac{u}{\pi w}\left(\frac{1}{\sqrt{1+(\frac{u}{\pi\cdot w})^2}}+\frac{1}{\sqrt{1+(\frac{1}{\pi\cdot w})^2}}\right)+\frac{3}{\pi}(1-u)-\frac{6v}{\pi}\right]}=k_{DH}D \qquad (5)$$

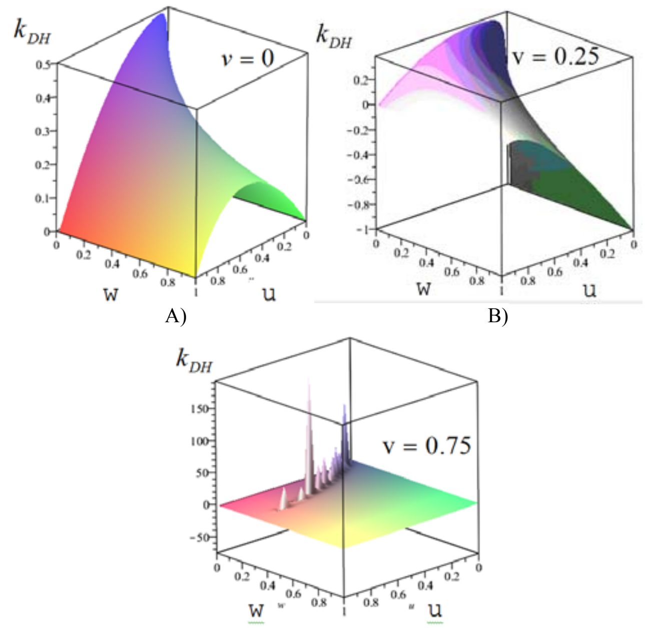
The graphs of B(u, w) and C(u, w), for the variations of: u = [0..1] and w= [0..100], are shown in Figure II.



A) B)

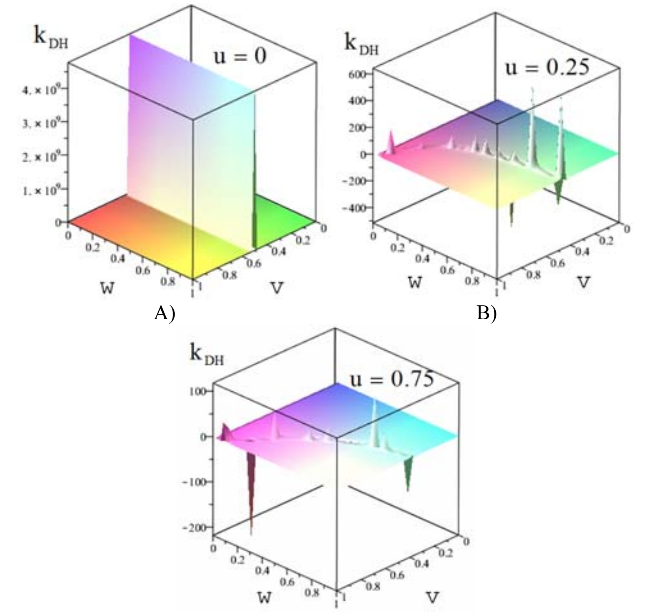
FIGURE II. A) THE GRAPH OF B(U, W); B) THE GRAPH OF C(U, W)

The dimensionless multiplication coefficient of the hydraulic diameter $k_{DH}(u,v,w)$ depends on the three variables. The graphs of the coefficient k_{DH} in function of two parameters and a given value of the third parameter, is shown in Figure III to V [6].



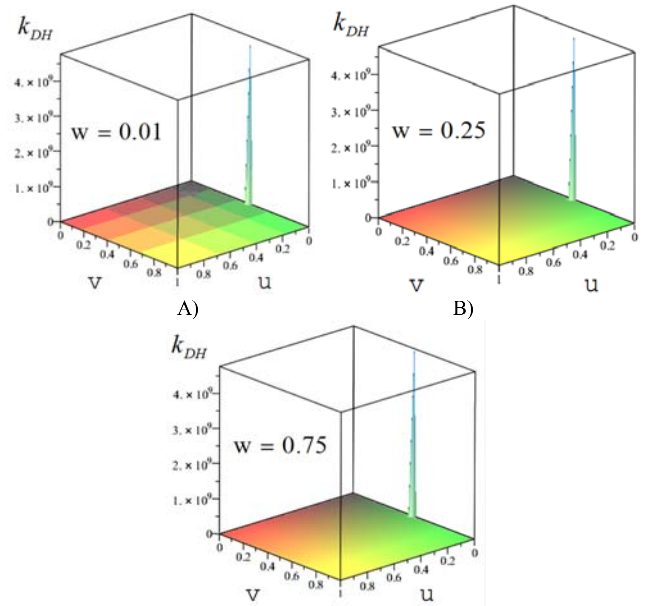
A) B) C)

FIGURE III. THE GRAPH OF KDH(W, U) FOR: A) V = 0; B) V = 0.25; C) V = 0.75



A) B) C)

FIGURE IV. THE GRAPH OF KDH(W, V) FOR: A) U = 0; B) U = 0.25; C) U = 0.75



A) B) C)

FIGURE V. THE GRAPH OF KDH(V, U) FOR: A) W = 0.01; B) W = 0.25; C) W = 0.75

The Reynolds number can then be calculated using equation [6]:

$$Re=\frac{4Q}{\nu D_H \pi}=4\frac{\left[\frac{u}{\pi w}\left(\frac{1}{C}+\frac{u}{B}\right)+\frac{3}{\pi}(1-u)-\frac{6v}{\pi}\right]}{\pi(1-u)\left[\frac{2u}{\pi(1-u)}(C-B)-\frac{6v}{\pi}\right]}\frac{Q}{\nu D}=k_{Re}\frac{Q}{\nu D} \qquad (6)$$

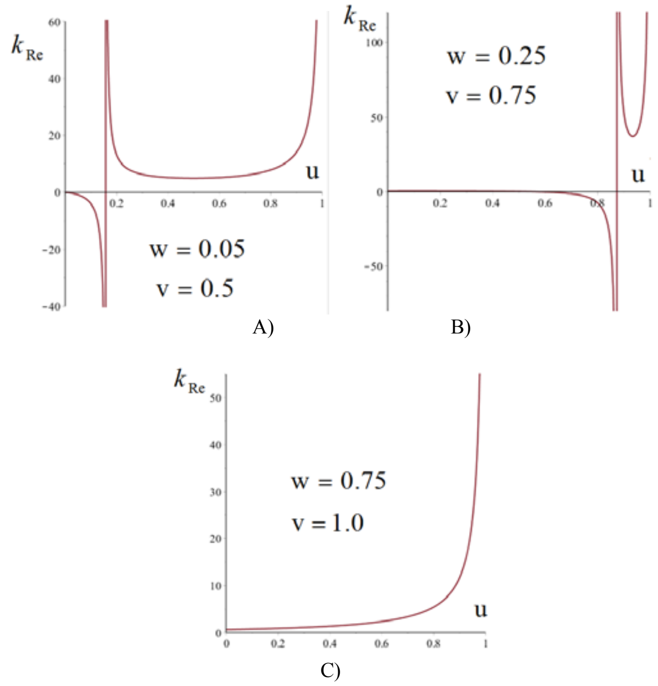


FIGURE VI. THE GRAPH OF KRE(U) FOR: A) W = 0.05, V = 0.5; B) W = 0.25, V = 0.75; C) W = 0.75, V = 1

The dimensionless multiplier coefficient noted with $k_{Re}(u, w, v)$ depends on the three variables. The graphs of the coefficient k_{Re} in function of two parameters and a given value of the third parameter, is shown in fig. VI [6].

The Darcy's equation can be used to calculate the uniform distributed longitudinally pressure drop [6]:

$$\Delta p = K_\lambda \lambda \frac{8\rho L Q^2}{\pi^2 D_H^5} \tag{7}$$

In this relation, the correction coefficient K'_λ is a correction coefficient of λ value corresponding to a central pipe with straight cross ribs:

$$K_\lambda = K'_\lambda \cdot A_1 \tag{8}$$

and

$$A_1 = 1 + 20 \cdot w^2 \tag{9}$$

The graph of A_1 is shown in Figure VII.

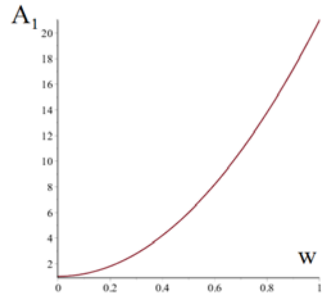


FIGURE VII. THE GRAPH OF A1(W)

The uniform distributed pressure drop on the pipeline can be calculated using the formula [6]:

$$\Delta p = \frac{\frac{1+20\cdot w^2}{4\pi^2(1-u)^5}\frac{K'_\lambda \rho \lambda L Q^2}{D^5}}{\left(\frac{\left[\frac{u}{(1-u)}\left(\sqrt{1+(\frac{u}{\pi\cdot w})^2} - u\sqrt{1+(\frac{1}{\pi\cdot w})^2}\right) - 3v\right]}{\left[\frac{u}{w}\left(\frac{1}{\sqrt{1+(\frac{u}{\pi\cdot w})^2}} + \frac{1}{\sqrt{1+(\frac{1}{\pi\cdot w})^2}}\right) + 3(1-u) - 6v\right]}\right)^5} = k_{\Delta p}\frac{K'_\lambda \rho \lambda L Q^2}{D^5} \tag{10}$$

where $k_{\Delta p}(u, v, w)$ depends on the three variables, in the range of u = [0..1], v = [0..1] and w = [0..1].

The graphs of the coefficient $k_{\Delta p}(u, v, w)$ in function of two parameters and a given value of the third parameter, is shown in Figure VIII [6].

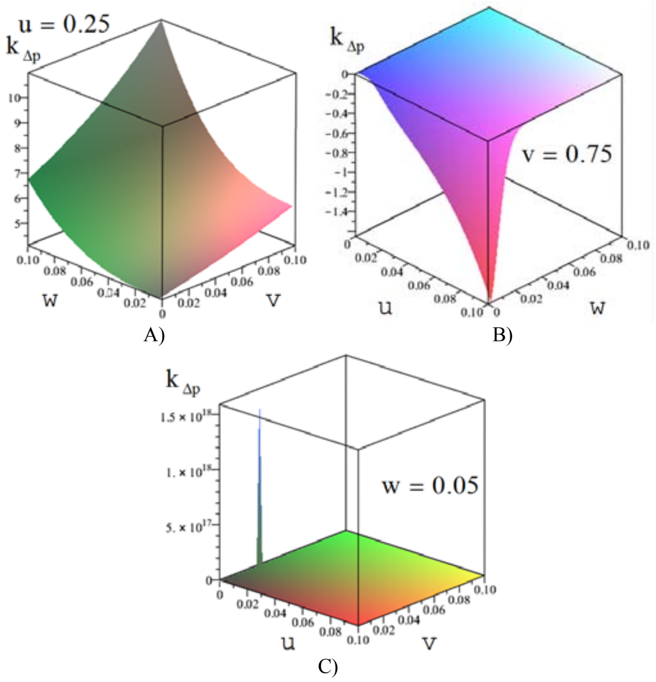


FIGURE VIII. THE GRAPH OF $k_{\Delta p}(u, v, w)$ FOR: A) U = 0.25; B) V = 0.75; C) W = 0.05

When the Reynolds number is low (Re ≤ 2000) the flow is laminar and formula for calculating the λ coefficient, for flow without thermal phenomena is as follows:

$$\lambda_L = \frac{16\pi\nu D(1-u)\left[\frac{2u}{\pi(1-u)}(C-B)-\frac{6v}{\pi}\right]}{Q\left[\frac{u}{\pi w}\left(\frac{1}{C}+\frac{u}{B}\right)+\frac{3}{\pi}(1-u)-\frac{6v}{\pi}\right]} = k_\lambda \frac{\nu D}{Q} \quad (11)$$

From the above formula the non-dimensional multiplier coefficient k_λ is:

$$k_\lambda = \frac{32(1-u)\pi\left[\frac{u}{w\pi^2(1-u)}\left(\sqrt{(w\pi)^2+(u)^2}-u\sqrt{(w\pi)^2+(d)^2}\right)-\frac{3v}{\pi}\right]}{\left[u\left(\frac{1}{\sqrt{(\pi w)^2+(u)^2}}+\frac{1}{\sqrt{(w\pi)^2+(d)^2}}\right)+\frac{3}{\pi}(1-u)-\frac{6v}{\pi}\right]} \quad (12)$$

The non-dimensional multiplier coefficient $k_\lambda(u,v,w)$ depends on the three variables. The graphs of the coefficient k_λ in function of two parameters and a given value of the third parameter, is shown in Figure IX.

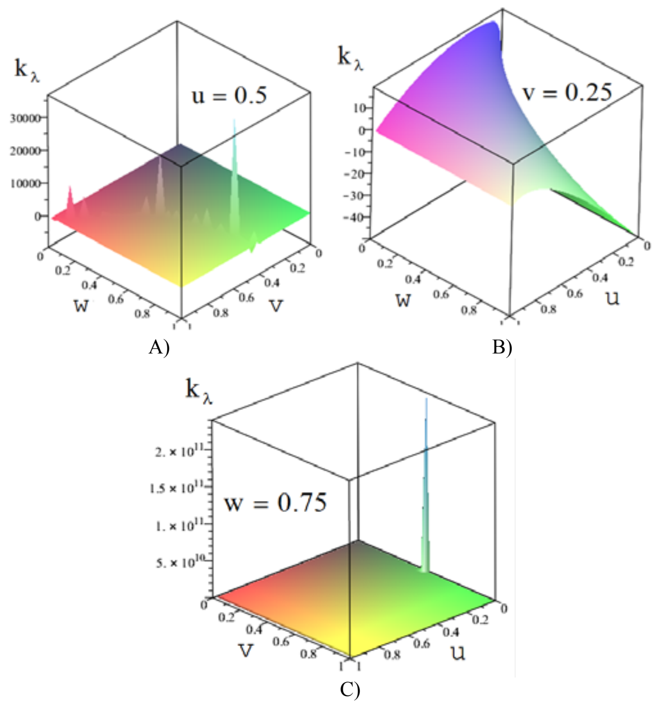


FIGURE IX. THE GRAPH OF K λ(U,V,W) FOR: A) U = 0.5; B) V = 0.25; C) W = 0.75

Finally, the uniform distributed pressure drop is calculated with the following formula:

$$\Delta p = \frac{1.36\cdot\left(1+20\cdot w^2\right)\frac{\rho\lambda_L L Q^2}{D^5}}{4\pi^2(1-u)^5\left(\frac{\left[\frac{u}{(1-u)}\left(\sqrt{1+\left(\frac{u}{\pi\cdot w}\right)^2}-u\sqrt{1+\left(\frac{1}{\pi\cdot w}\right)^2}\right)-3v\right]}{\left[\frac{u}{w}\left(\frac{1}{\sqrt{1+\left(\frac{u}{\pi\cdot w}\right)^2}}+\frac{1}{\sqrt{1+\left(\frac{1}{\pi\cdot w}\right)^2}}\right)+3(1-u)-6v\right]}\right)^5} \quad (13)$$

III. Numerical Calculation Program

Based on the proposed mathematical algorithm a computational program was elaborated using Maple 2016 software [17] as follows:

```
# Initial data
> rho:= ; Q :=; D0:=; d0:=; nu:= ; L:= ; b0 :=;
# Calculated values
> u := d0/D0;
> v := b0/D0;
> w := d0/L;
> K_L:=1.36*A1;
> C := (1+(u/(Pi*w))^2)^.5;
> B := u*(1+(1/(Pi*w))^2)^.5;
```

```
>DH:=D0*(1-u)*(2*u*(C-B)/(Pi*w*(1-u))-6*v/Pi)/(u*(1/C+u/B)/(Pi*w)+3*(1-u)/Pi-6*v/Pi);
> A1 := 20*w^2+1;
> d := DH;
> Rey := evalf(4*Q/(Pi*d*nu));
> vm := 4*Q/(Pi*(D0^2-d0^2));
> if Rey < 2000 then Lambda0:= 64/Rey end if;
> if Rey <= 2000 then RC := Regim_de_curgere_*laminar
end if;
> Lambda := Lambda0;
> if RC= Regim_de_curgere_*laminar then Deltap:= (1/2)*rho*K_L*Lambda*L*vm^2/DH end if;
```

IV. Conclusions

The present paper describes an efficient and easy-to-implement method to determine the pressure drop in industrial pipes with non-uniform roughness and helical ribs in the case of laminar flow. Identification of the flow regime is achieved in order to establish the correct pressure drop and the calculation of physical values related to the flow process or the pipe dimensional sizes. The results can be used in various fluid flow applications by engineers and researchers.

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[16] *** AutoCAD 2017 software.

[17] *** Maple 2016 software.