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Characterization of Hydraulic Fluids and Development of Heat Transfer Correlation in Helical Coil using New Dimensionless Number M

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Abstract — The heat transfer rate in helical coils is higher than in straight tube due to secondary motion developed. The characterization of fluid flow in helical coil is very difficult due to complex flow pattern. In this experimental work, an innovative approach for the characterization of fluid flow and development of heat transfer correlations in helical coil for Newtonian fluids using new dimensionless Number M is presented. Experiments were conducted under isothermal and non-isothermal conditions for the development of innovative heat transfer correlations. Three helical coils of different coil curvature ratios are used in this work. The innovative correlations were validated using work of earlier investigators and are found to be satisfactory.

Keywords — Hydraulic Fluids, Heat Transfer Correlation

I. Introduction

It has been extensively reported that heat transfer rate in helical coils are higher than heat transfer in straight tube for same experimental conditions. Mainly, in chemical industries, the process of improving convective heat transfer is referred to as heat transfer enhancement or intensification. Various heat transfer enhancement methods like active and passive techniques have been used to improve heat transfer in chemical reactors, heat exchangers and in flow systems for several decades. As a result of its compact structure and higher heat transfer coefficient, helical coil heat exchangers are popularly used in industrial applications such as refrigeration and air conditioning, nuclear industries, food processing and power generation etc.

The critical Reynolds numbers introduced by few authors to identify the transition from laminar to turbulent flow in helical coils did not fix any limit up to which laminar flow persists for Newtonian as well as non-Newtonian types of fluid flow except M number. This is important to understand transition phase of fluid in coil. The correlations developed to determine critical Reynolds number to characterize the hydrodynamics of fluid flow in helical coils by various investigators are listed in Table 1. It can be seen from Table 1 that as δ increases, critical Reynolds number also increases. Then question arises, what is the final limit on critical Reynolds number up to which laminar flow persists.

Ito [1] has given limit of critical Reynolds number for Newtonian fluid as 10,000 for laminar flow but this does not remain constant for all the curvature ratios.

Table 1. Represents the name of investigators and their criteria developed

Name of Investigator	Criteria developed	Range of Parameters
Ito H. [1]	$Re_{cr} = 2000\ (1+13.2\ \delta^{0.6})$	$5.10 \times 10^{-4} \leq \delta \leq 0.2$
Srinivasan et al. [2]	$Re_{cr} = 2100\ (1+12\ \delta^{0.5})$	$9.70 \times 10^{-3} \leq \delta \leq 0.135$
Cioncolini et al. [3]	$Re_{cr} = 30000\ \delta^{0.47}$	$0.0416 \leq \delta \leq 0.143$
Ito H. [4]	$Re_{cr} = 2000\ \delta^{0.32}$	----------------------------
Schmidt E. F. [5]	$Re_{cr} = 2300\ (1+8.6\ \delta^{0.45})$	----------------------------

For smaller value of δ, centrifugal force plays lesser role for developing secondary motion which suppresses the turbulence to smaller extent and hence smaller threshold Reynolds number. Decreasing values of δ results into smaller critical Reynolds number which approaches towards the straight tube and it is practically true. Only M number gives fix value as M = 2100 for any types of fluid and for any curvature ratios up to which laminar flow persists in helical coil like Reynolds number, Re = 2100 for laminar flow in straight tube. Hence, M number is significant to characterize the hydrodynamics of fluid flow in helical coils for any types of fluids and any curvature ratios.

II DIMENSIONLESS NUMBER M

Mujawar and Rao [6] established for the first time, the criteria for laminar flow in coiled tubes on the basis of a new dimensionless number, M, deduced from a knowledge of the effect of coil curvature ratio on the flow curves. Based on their experimental results, the criteria for laminar flow in coiled tubes for any type of fluid, either Newtonian or non-Newtonian and for any practical coil curvature ratio is given in generalized form as:

$$M = \frac{\mathrm{Re}, gen_c}{\left(a/R\right)^{m_c'}} \leq 2100 \qquad 1$$

These rheological constants were determined experimentally in coiled tubes for water as Newtonian fluid, and CMC and sodium alginate as non-Newtonian fluids in laminar flow regimes. They proved based on their experimental results that up to M ≤ 2100, the laminar flow persists for both types of fluids. For Newtonian fluids, the equation (1) is simplified to set the criterion for laminar flow based on their experimental data as:

$$M = \frac{\mathrm{Re}^{0.64}}{0.26\left(a/R\right)^{0.18}} \leq 2100 \qquad 2$$

The criterion for laminar flow in coiled tubes given by equation (1) was satisfactorily tested with the results of their work. However, Mujawar and Rao [6] could not develop heat transfer correlations relating Nusselt number to M number in their research work. Hence, this present work was undertaken to develop generalized heat transfer correlations in terms of M number, Prandtl number and coil curvature as a direct function of Nusselt number and validation of this developed correlation with work of earlier investigators.

III EXPERIMENTAL SET UP

Experimental set up and its procedure is explained in details by Pawar and Sunnapwar [7].

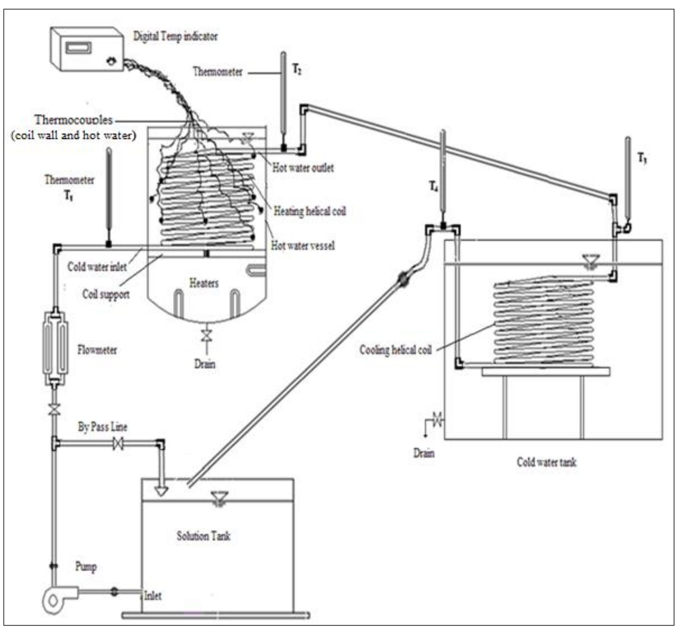

Fig. 1 Type-III experimental setup

Table 2 Physical dimensions of helical coils used

Helical Coils	δ	L	D_o	D_i	d_i	d_o	N	Pitch
Coil-I	0.0757	8195.47	300	274.6	20.8	25.4	9.5	29.15
Coil-II	0.064	9687.73	350	324.6	20.8	25.4	9.5	29.15
Coil-III	0.055	11179.98	400	374.6	20.8	25.4	9.5	29.15

The thermo physical properties of water flowing inside the helical coil test section were assumed constant along the coil length, and evaluated at mean bulk temperature. The heat transfer data analysis was carried out as per methodology given by Pawar and Sunnapwar [7].

IV. RESULT AND DISCUSSION

4.1 Development of Heat Transfer correlation using M number

The correlations (3) is proposed based on overall experimental data generated from 183 tests conducted for Newtonian fluids including Type-I to Type-III experimental setup under isothermal and non-isothermal conditions covering laminar to turbulent flow regimes as shown in figures 2. Fig.2 shows the development of correlation (3) with (a/R) parameter having coefficient of correlation, R = 94.35%.

The overall correlation including (a/R) parameter for the tests data (183) under isothermal and non-isothermal temperature condition is as follows:

$$Nu = 0.0103(M)^{1.2314}\,\mathrm{Pr}^{0.4}\left(\frac{a}{R}\right)^{0.5438} \qquad 3$$

valid for the range; 850 ≤ M ≤ 4643, 3.83 ≤ Pr ≤ 7.308 and 0.055 ≤ (a/R) ≤ 0.0757.

4.2 Validation of innovative correlation (3) with the work of earlier Investigators

The innovative correlation (3) is compared with the work of Jayakumar et.al [8] and Xin and Ebadian [9]. The equation (3) gives average Nusselt number as 45.78 whereas Jayakumar et al. [8] gives 44.54 and Xin and Ebadian [9] as 50.64. The developed correlation shows deviation within acceptable range of industrial practices for design of helical coil heat exchangers. Hence, the developed correlations are recommended with full confidence for the design of helical coil heat exchangers within specified conditions. Similarly, several heat transfer correlations were developed under isothermal conditions covering laminar to turbulent flow regimes using Newtonian and non-Newtonian fluids and validated with the work of earlier investigators. Hence, M number is strongly recommended for characterization of fluids in helical coil heat exchangers for Newtonian as well as non-Newtonian fluids.

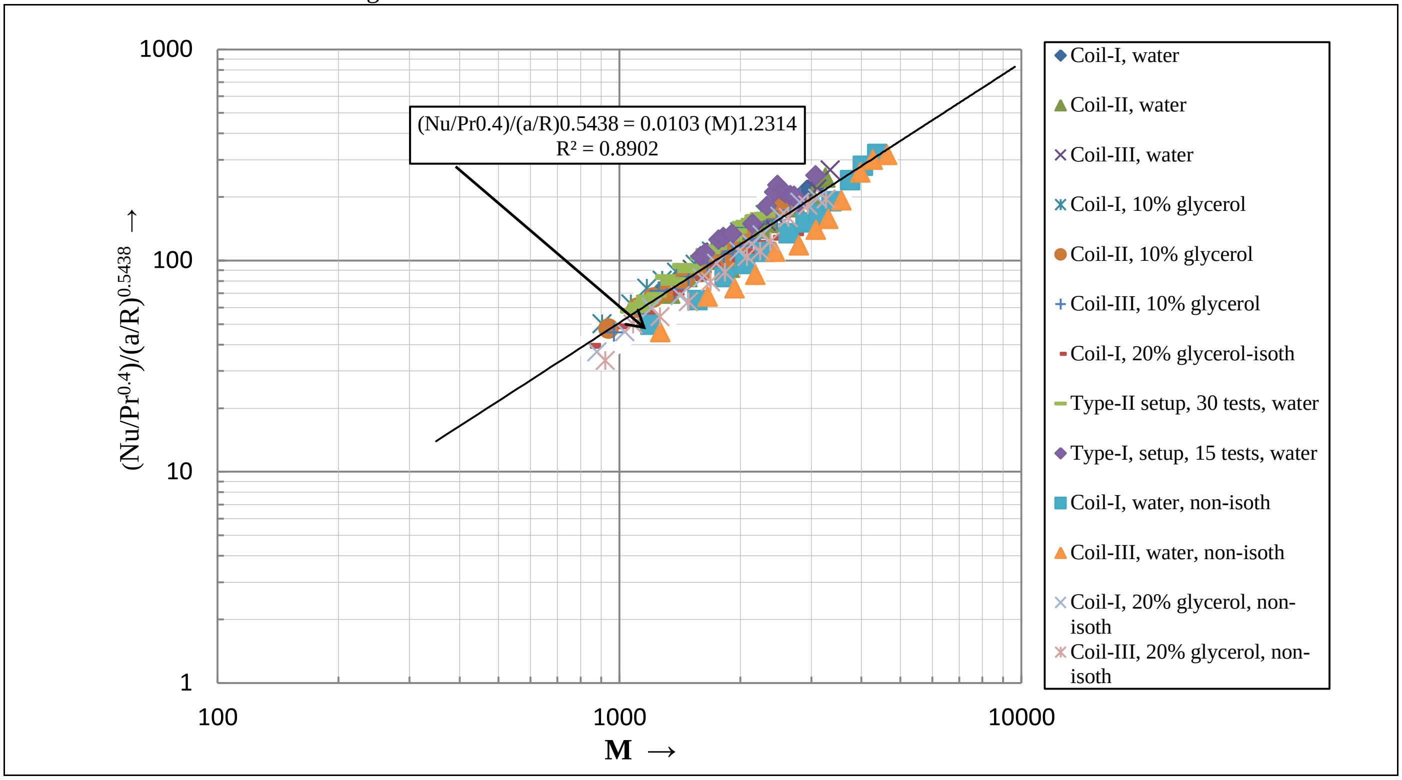

Fig.2 A logarithmic plot for the development of overall correlation using data of 183 tests for Newtonian fluids with (a/R) parameter under isothermal and non-isothermal conditions.

V. CONCLUSION

From exhausting literature survey, it is seen that there is no evidence of heat transfer correlation in helical coil using new dimensionless number M which is significant for characterization of Newtonian as well as non-Newtonian fluids. Hence, 183 experiments were performed using Newtonian fluids like water, 10 % and 20 % glycerol water mixture under isothermal and non-isothermal conditions covering laminar to turbulent flow to development innovative heat transfer correlation for the first time, equation (3). The developed correlation was compared with the work of earlier investigators and was found to be in good agreement. Future work can be done using non-Newtonian fluids and study of flow physics using CFD package for large range of parameters under various temperature conditions.

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