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Laminar Flow Heat Transfer of a Pseudoplastic Fluid through a Double Pipe Heat Exchanger

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Abstract
An experimental study was carried out to obtain the mean convective heat transfer coefficient of aqueous carboximethyl cellulose (CMC) solutions in double-pipe heat exchangers. Co-current and counter- flows were considered in the investigation. From the experimental data a Nusselt number was calculated for a wide range of Graetz number, Reynolds number, and CMC concentrations. Increasing the Graetz and Reynolds numbers promote the heat transfer and variation of CMC concentration has a noticeable effect on the Nusselt number.

Keywords: *Non-Newtonian Fluids, Double-pipe Heat Exchanger, Nusselt Number, Greatz Number, Experimental*

Introduction
Heat transfer processing of viscous non-Newtonian fluids is encountered in various industrial sectors including chemicals, petro-chemicals, food, polymers, and phar-maceuticals. For these processes heat transfer is one of the key components of the flow loop and for reliable design of such equipment it is necessary to have enough information about the thermal behaviour of the processing fluid. Most of the research activities on heat transfer in the literature are related to Newtonian fluids while non-Newtonian fluids have received less attention from researchers. Non-Newtonian fluids exhibit a non-linear relation between shear stress and shear rate. The simplest model of non-Newtonian fluids is the power law model of Ostwald and de Waele which can be used for intermediate ranges of the shear rate. Commonly encountered non-Newtonian fluids such as polymer solutions, paper pulps, detergents, oils, and greases can be classified by the pseudoplastic model which is specific case of the power law equation when $n<1$.
Comperehensive literature reviews on non-Newtonian fluid flow and heat transfer have been published by Skelland [1], Metzner [2], Lawal and Mujumdar [3], and Etemad [4]. Yoo [5] measured heat tarnsfer of non-Newtonian turbulent flow through circular tube with constant heat flux boundary condition. Joshi and Bergles [6] and Scirocco et al. [7] did an experimental investigation related the to laminar flow of pseudoplastic solutions in a circular tube subjected to a uniform wall heat flux. The results of Scirocco et al. [7] cover the turbulent regime

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as well.

Most of the previous results were obtained for two ideal constant wall temperature and constant wall heat flux thermal boundary conditions. For heat exchangers the actual thermal boundary condition is different while wall temperature as well as wall heat flux vary along the heat exchanger tubes.

Due to the lack of sufficient information related to the heat transfer of pseudoplastic fluids through double pipe heat exchangers the present investigation was conducted to evaluate the heat transfer performance of the heat exchanger in co-current and counter current situations.

Experimental Set up

A schematic diagram of the experimental set up is shown in Figure 1. The system consists of a pump, a heater, a measuring tank, a double pipe heat exchanger, valves, and thermocouples. The main part of the closed flow loop system is the double pipe heat exchanger. This section contains two co-axial tubes both made of copper with an effective length of 91 cm. The inner tube possesses 11.3 mm inside diameter with a 1.4 mm wall thickness. The gap between two coaxial tubes is 1.7 mm. The non-Newtonian fluids flow through the inner tube while water as a coolant flows inside the annular space. The fluid passes a length of 6.5 cm before entering the test section which permitts attainment of fully developed conditions at the inlet of the test section.

The non-Newtonian fluids were the solutions of carboxymethylcellulose (CMC) with different concentrations. The aqueous solution of CMC was prepared using the commercial grade of CMC. The powder was dissolved in distilled water very gently using a proper agitator to avoid agglomeration of the powder. The rheological behavior of CMC solutions was obtained using a coaxial rotational rheometer. The rheometer was connected to a temperature control bath to enable obtaining the rheological data at different temperatures. The consistency and power law indices of CMC solutions obtained by rheometer are shown in Table 1. The experimental results confirm the validity of the pseudoplastic model for CMC solutions.

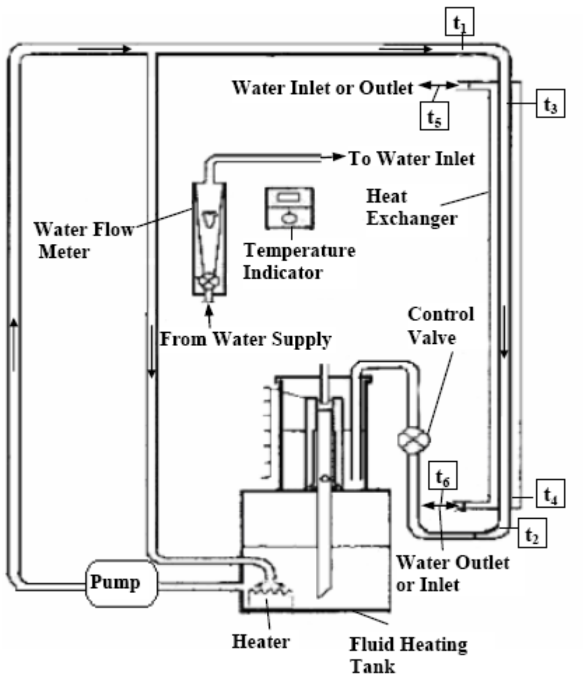

Figure 1. Schematic diagram of the experimental set up

Table 1. Consistency and power law indices of CMC solutions

CMC Solution Concentration /ppm	n	kPa.secn
200	0.927	0.00511
500	0.8229	0.00849
1000	0.7889	0.01235
1500	0.7254	0.01968
2000	0.7051	0.02792
3000	0.6509	0.04453
4000	0.6161	0.06572
4500	0.6002	0.08433
6000	0.578	0.10530
8000	0.5549	0.12356

The working fluid is circulated through the loop by a small centrifugal pump. The bulk temperatures of the non-Newtonian fluid and water and the wall temperature of the inside tube at both the inlet and outlet sections are measured using six K-type thermocouples connected to a digital temperature indicator with ± 0.05 ^oC accuracy. The test section is thermally isolated using different isolators to eliminate any possible heat transfer to the environment. The non-Newtonain fluid is heated in a heating tank before entering the heat exchanger. This tank is equipped by electrical heater and a thermostat is used to control the fluid temperature to prevent overheating. The fluid heating tank eliminates fluctuations in the flow rate at the inlet of the pump and also helps to the degassing of the working fluid. Tab water flows in the annular space between the two coaxial tubes and two co-current and counter-current modes can be experienced by changing water flow direction. The flow rate of non-Newtonian fluids is determined by measuring the weight of the fluid flowing in a given time while the flow rate of water is obtained using a calibrated rotameter.

Data Processing

The non-Newtonain fluid is cooled by water and the rate of heat transfer for CMC solution can be obtained by the following equation:

$$q = \dot{m} c_p (t_1 - t_2) \quad (1)$$

where $\dot{m}$, c_p, t_1 and t_2 represent mass flow rate, heat capacity, inlet and outlet temperatures of the solution respectively. The convection heat transfer coefficient is obtained from an energy balance applied to the tube using the measured wall and bulk temperatures.

$$q = hA\theta_m \quad (2)$$

where A is heat transfer area and θ_m is the logaritmic mean temperature difference between the tube wall and the solution.

$$\theta_m = \frac{(t_1 - t_3) - (t_2 - t_4)}{\ln \frac{t_1 - t_3}{t_2 - t_4}} \qquad (3)$$

t_3 and t_4 are tube wall temperatures at the inlet and outlet respectively. The Nusselt number is defined as:

$$Nu = \frac{hd}{K} \qquad (4)$$

where d is the inside diameter of the central tube and K is the thermal conductivity of the CMC solution. In this equation Nu represents the average Nusselt number over the whole length of the tube. The density, thermal conductivity and heat capacity of the CMC solutions are close to those properties of distilled water [8]. The following various dimensionless groups are used in the analysis of experimental data:

$$Re = \frac{\rho v^{2-n} d^n}{k}, \quad Pr = \frac{k C_p \left(\frac{v}{d}\right)^{n-1}}{K}, \quad Gz = \frac{\pi d \, Re \, Pr}{4l} \qquad (5)$$

In these equations ρ, v, d, K, and l are density, fluid average velocity, tube diameter, thermal conductivity, and tube length respectively.

Results and Discussion

Co-current flow

The variation of the Nusselt number with Gz^{-1} for different CMC concentrations are presented through figures 2 and 3. Based on the experimental data, the reduction of the Graetz number decreases the Nusselt number which is valid for all CMC solutions. This is due to the high temperature difference of the streams at the inlet of the channel. A strong influence of the Graetz number on the value of the Nusselt number occurs in the higher Graetz numbers. From figures 2 and 3 at a constant Graetz number pseudoplasticity of the solution (CMC concentration) has a pronounced effect on heat transfer which is reflected in the Nusselt number variations. This is due to the dual effects of CMC concentrations on the velocity profile and apparent viscosity. Increasing CMC concentrations results in a lower power law index and consequently a thinner boundary layer which causes a higher difference of wall temperature gradient and a higher Nusselt number while higher concentration increases apparent viscosity which diminishes the heat transfer rate. The total effects of these variations are included on the value of the Nusselt number. Figures 4 and 5 show the effect of the Reynolds number on the the Nusselt number. Increasing the Reynolds number promotes the Nusselt number which is due to the higher solution flow rate and therefore the dominant role of convective heat transfer in the case of a higher Reynolds number.

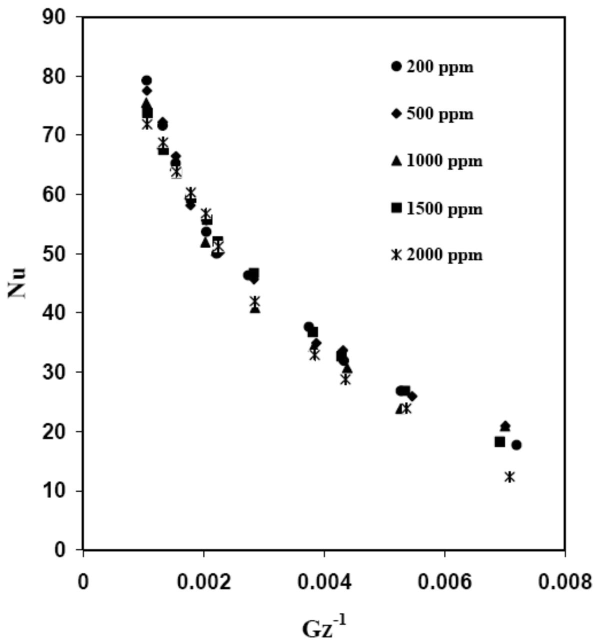

Figure 2. Nu vs. Gz^{-1} for co-current flow and CMC concentration of 200-2000 ppm

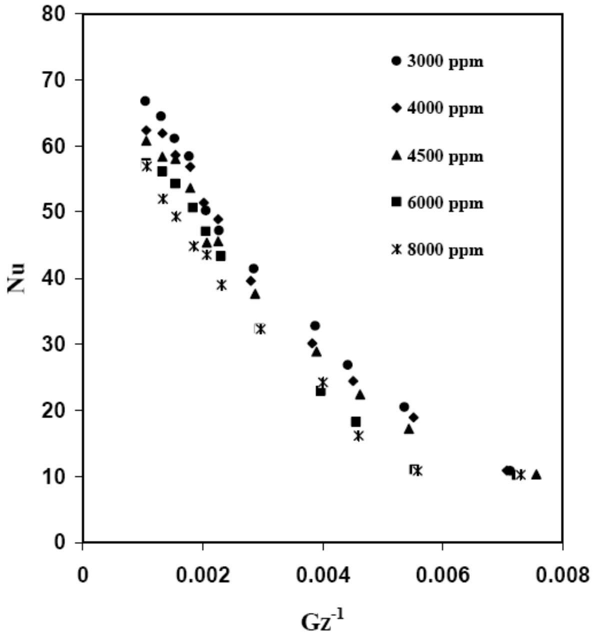

Figure 3. Nu vs. Gz^{-1} for co-current flow and CMC concentration of 3000-8000 ppm

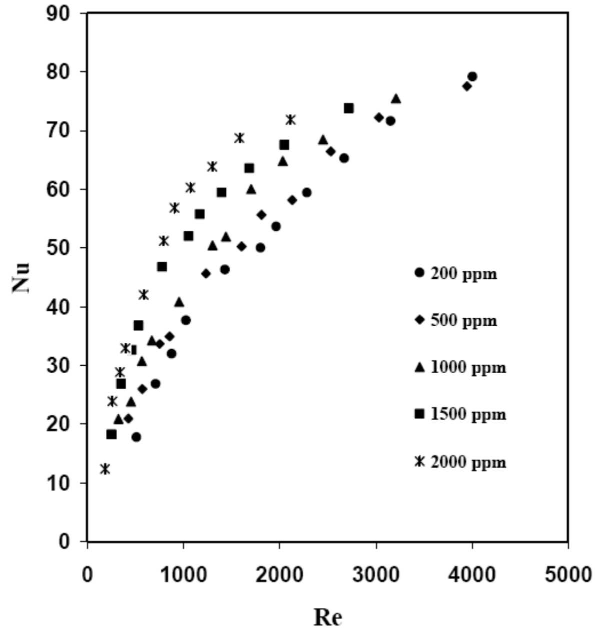

Figure 4. Nu vs. Re for co-current flow and CMC concentration of 200-2000 ppm

Counter current flow

Figures 6 and 7 illustrate the variation of the Nusselt number with the reverse of the Graetz number and the effect of the Reynolds number on heat transfer is presented by figures 8 and 9. The explanation of the curves is similar to the case of co-current flow. The results indicate that for counter current flow at the same Re, Nusselt number is almost lower than that of co-current flow for the same CMC concentration.

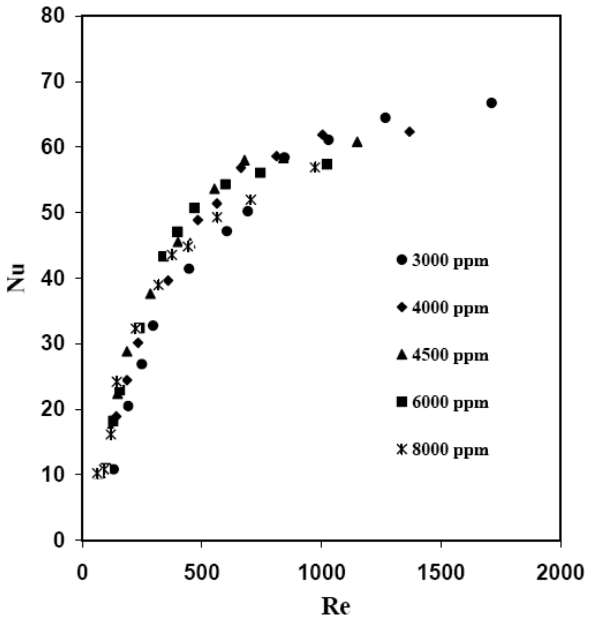

Figure 5. Nu vs. Re for co-current flow and CMC concentration of 3000-8000 ppm

The error analysis technique was used to evaluate the accuracy of the results. The maximum relative errors of logaritmic mean temperatue difference, mass flow rate, heat transfer rate, and the Nusselt number were 1.99%, 5.33%, 8.85%, and 10% respectively.

Conclusions

An experimental investigation was done to study the heat transfer coefficient in double pipe heat exchangers in co-current and counter current situations. The results were obtained for the CMC solutions with different concentrations. The power law index, Graetz number, and Reynolds number showed pronounced effects on the Nusselt number. Increasing the Graetz number enhances heat transfer and the Nusselt number is influencecd by the variation of concentration for both co-current and counter current cases. For a specific CMC concentration increasing the Reynolds number causes the promotion of heat transfer.

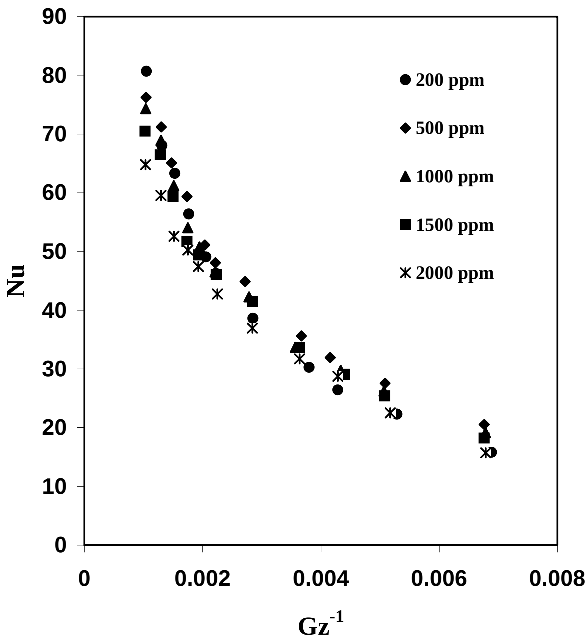

Figure 6. Nu vs. Gz^{-1} for counter current flow and CMC concentration of 200-2000 ppm

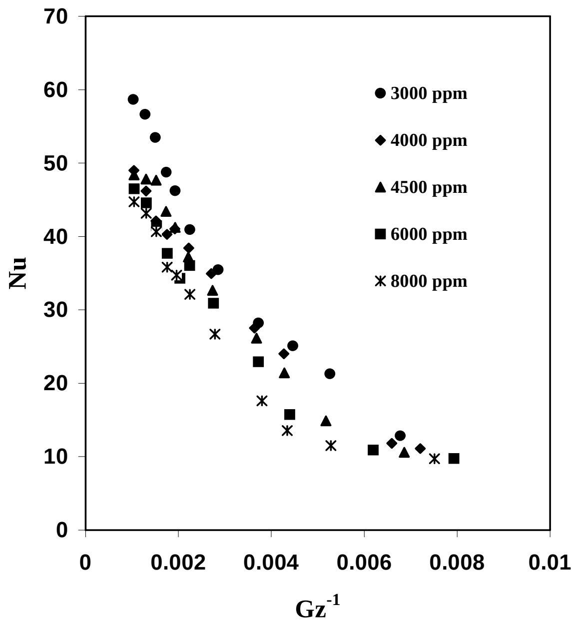

Figure 7. Nu vs. Gz^{-1} for counter current flow and CMC concentration of 3000-8000 ppm

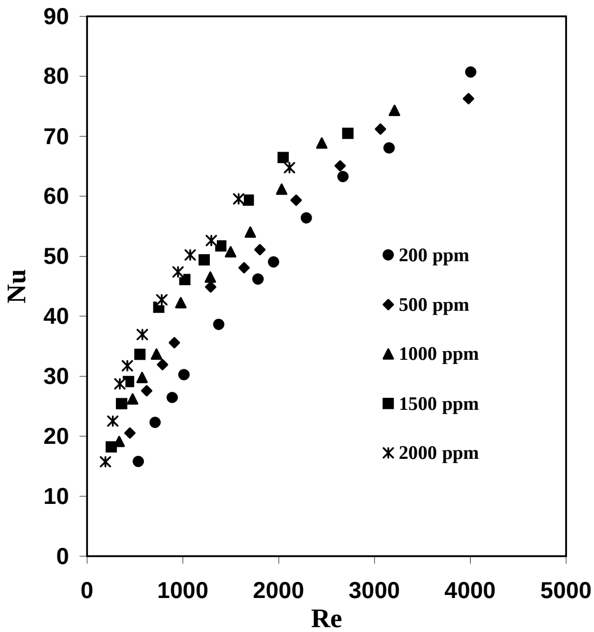

Figure 8. Nu vs. Re for counter current flow and CMC concentration of 200-2000 ppm

Acknowledgement

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Nomenclature

A	Heat transfer area
Cp	Heat capacity
d	Inside diameter of central tube
Gz	Graetz number
h	Convection heat transfer coefficient
k	Consistency index
K	Thermal conductivity
L	Tube length
$\dot{m}$	Mass flow rate
n	Power law index
Nu	Nusselt number

Pr Prandtl number

q Heat transfer rate

Re Reynolds number

t Temperature

v Fluid average velocity

Greek Symbols

θ Temperature difference

ρ Density

Subscripts

m Logaritmic mean

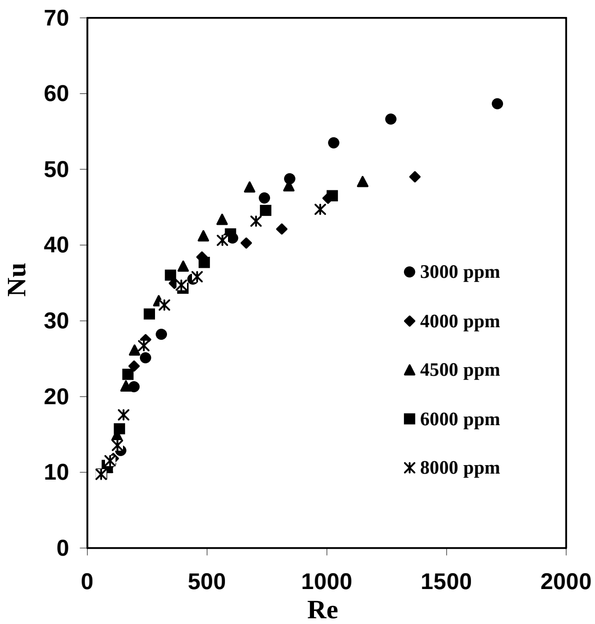

Figure 9. Nu vs. Re for counter current flow and CMC concentration of 3000-8000 ppm

References

1. Skelland, A.H.P., "Non-Newtonian flow and heat transfer", John Wiley & Sons, (1967).
2. Metzner, A.B., Vaughn, R.D., Houghton, G.L., "Heat transfer to non-Newtonian fluids", *AIChE Journal*, **3** , 92(1957).
3. Lawal, A., Mujumdar, A.S., "Laminar duct flow and heat transfer to purely viscous non-Newtonian fluids", in: A.S. Mujumdar, R.A. Mashelkar (eds), Advances in transport processes, Wiley Eastern, New Dehli, 352 (1989).
4. Etemad, S.GH., "Forced convective heat transfer of non-Newtonian fluids in tubes", *Esteghlal*, **1**, 1 (1998).
5. Yoo, S.S., "Heat transfer and friction factors for non-Newtonian fluids in turbulent pipe flow", Ph.D. thesis, University of Illinois, Chicago, IL (1974).
6. Joshi, S.D., Bergles, A.E., "Experimental study of laminar heat transfer to in-tube flow of non-Newtonian fluids", *Journal of Heat Transfer*, **102**, 397 (1980).
7. Sciroco, V., Devienne, R., Lebouche, M., "Laminar and turbulent flow of a pseudoplastic fluid in a circular conduit: heat transfer coefficients", *International Chemical Engineering*, **31**(3), 450 (1991).
8. Cho, Y.I., Hartnett, J.P., "Non-Newtonian fluids", in: W.M. Rohsenow, J.P. Hartnett, E.N. Gonic (Eds), Handbook of heat transfer applications, McGraw-Hill, (1985).