

Study of Motor Oil Cooling at Low Reynolds Number in Multi-Port Narrow Channels

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ABSTRACT

Mini and micro-scale channels have drawn researchers' attention in the past three decades. The use of these tiny channels in a heat exchanger is considered as one of the pioneered works on the narrow channels as minichannels provide high heat transfer rates per unit volume. Motor oil, known as engine oil, is one of the vital fluids in automotive applications. Its cooling process is confronted by its thermo-physical properties, especially viscosity, which makes this process difficult.

In current investigations, experimental endeavors have been performed using a closed loop thermal wind tunnel to verify the aptness of cooling the motor oil through a cross-flow minichannel heat exchanger. The prototype heat exchanger consists of 3 circuits; each circuit has five slabs which are connected to each other by four serpentine. There are 68 channels of 1 mm circular diameter drilled through each slab. The minichannel heat exchanger comprises of wavy fins arranged parallel to the flow of air. The inlet temperature of the motor oil was kept constant at 75°C while the air inlet temperatures were varied within the range of 20°C and 40°C.

The flow of the oil fell in the laminar regime due to its high viscosity, which consequently resulted in low Reynolds numbers (Re). The range of Re was found to be from 0.85 to 3.5 whereas the air flow rates were between 6 m/s and 18 m/s. Correlations were developed between the oil Nusselt number and oil Re and Prandtl numbers. The effect of Re on the heat transfer coefficient, NTU , and effectiveness were investigated. The results were compared with the findings of another highly viscous fluid where a similar test specimen was used and same trends were observed.

KEYWORDS: Minichannel heat exchanger, Motor oil, Heat transfer, Thermo-physical properties, Reynolds number, Thermal wind tunnel

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1. INTRODUCTION

Investigations using small channels in compact heat exchangers have recently gained a great deal of interest. The utilization of minichannels has led the compact heat exchanger to even more advanced compactness to reach a higher heat transfer rate, and to obtain lighter system. Even though there has been a straightforward guide for expressing the dimensional range of the channel size, which is based on hydraulic diameter, there have been distinct views on the dimensional categorizations of channels. For example, Mehendale *et al.* [1] classified the range from 1 to 100 μm as minichannels, 100 μm to 1 mm as meso-channels, 1 to 6 mm as compact channels, and larger than 6 mm as conventional channels. On the other hand, Kandlikar and Grande [2] stated

that channels having hydraulic diameter between 200 $\mu\text{m} < Dh \leq 3 \text{ mm}$ are called minichannel.

The minichannel has gained interest in the last three decades because of the downsizing of the thermal devices used in various aspects of everyday life. The cooling of the very large scale integrated (VLSI) circuits, biomedical applications, micro-heat-exchangers are some examples of the fundamental ideas of the minichannel heat transfer and fluid flow and why they are considered essential for proper design. Utilizing minichannels as a cooling medium is a technique of forced convection cooling, which is accomplished by forcing liquid through miniature channels. In 1981, the micro-scale channel cooling theory was initiated by Tuckerman and Peace [3]. They managed to dissipate heat, of a flux of rate 790 W/cm², by utilizing a water-cooled

heat sink. Phillips [4] widened the investigation and developed flow friction and Nusselt number (Nu) correlations by taking into consideration both laminar and turbulent regimes. It is important to mention that Tuckerman and Phillips' studies were based on macroscale correlations and the effects of microscale were not considered. Later, many researchers conducted experimental and numerical investigations to broaden the understanding of the heat transfer phenomenon in microscale channels.

One of the recent developments of these studies is to minimize the size of the heat exchanger, particularly the size of tubes or channels, to even a nanoscale. Therefore, the literature found on this development is relatively limited compared to the conventional heat exchangers. During the last thirty years, the investigation of the miniature heat exchanger has become overly popular that almost all aspects of fluid flow and heat transfer characteristics have been examined. Following criteria have been considered from literature research area to evaluate and validate the outcomes of the current investigation:

- The flow regime inside the channel is laminar ($Re < 2000$).
- The type of the fluid is single-phase liquid flow.
- Both experimental and numerical investigations are considered.
- The size of channel, which is based on the hydraulic diameter, is $10 \mu m \geq D_h \geq 6 mm$.
- Due to the limited studies made on the circular cross-sectional shape, studies done on rectangular and trapezoidal channel shapes are also included in the literature review.

Several experimental and numerical works [5,6,7,8,9,10,11,12,13,14,15,16] in the literature have shown that the fluid flow and heat transfer characteristics of micro-scale channels depart from the well-known macro-scale correlations and equations. Choi *et al.* [5] calculated the convective heat transfer coefficients for flow of nitrogen gas in circular microtubes. The hydraulic diameter of these microtubes ranges from 3 to 81 μm . They found that the measured Nu in laminar flow is a strong function of the Reynolds number. This result contrasts with the conventional prediction for fully developed laminar flow, in which the Nu is constant.

Qu *et al.* [6] experimentally examined the convective heat transfer of water flowing through trapezoidal silicon microchannels with a hydraulic diameter ranging from 62 to 169 μm . The authors also performed a numerical analysis, which was validated with their experimental results. It was found that the numerical Nu in laminar regime are higher than the predicted ones by the experimental study. They attributed this discrepancy to the effect of surface roughness (i.e. roughness viscosity) on walls of the microchannels.

Wu and Cheng [7] experimentally investigated the heat transfer phenomenon of de-ionized water in 13 different trapezoidal silicon microchannels ($D_h = 25.1 - 291 \mu m$). It

was demonstrated that the values of the Nu depends greatly on different geometric parameters (height-to-top width ratio and bottom-to-top width ratio). The authors concluded that the laminar convective heat transfer showed two different characteristics at low and high Reynolds number ranges. At low Re ($0 < Re < 100$), the Nu increases sharply with the increase of Re . In contrast, the Nu mildly increases for $Re > 100$.

As the size of a flow channel gets smaller and smaller, wall effects on fluid flow and heat transfer become significant. The traditional continuum assumption in flow analysis cannot be held valid in very small channel flows.

One way to verify the applicability of the continuum assumption is by calculating a dimensionless number, called the Knudsen number (Kn). It is defined as the ratio of the fluid molecular mean free path (λ) to the characteristic length of the flow field, which is the channel hydraulic diameter (D_h).

$$Kn = \frac{\text{fluid molecular mean free path}}{\text{Characteristic length}} = \frac{\lambda}{D_h} \quad (1.1)$$

where

$$\lambda = \frac{\mu\sqrt{\pi}}{\rho\sqrt{2RT}} \times 10^6 [\mu m]$$

where R , T , ρ , and μ represent the universal gas constant [J/kgK], temperature [K], density [kg/m³], and dynamic viscosity [kg/m.s] respectively.

For gas flows, the degree of rarefaction and the applicability of traditional flow models can be determined by Kn . As Kn approaches to 0, near-equilibrium, continuum flows can be described by the Navier-Stokes ($N-S$) equations. However, for Kn greater than 0.1, the $N-S$ equations fails, and alternative continuum models are needed; for Kn greater than 10, free-molecule solutions are used. For liquid flows, it is very difficult to find out a clear demarcation for the breakdown of the $N-S$ equations [1].

Morini [9] stated that the distance between the molecules in liquids is usually much smaller than that for gases, leading to even a smaller value of the Kn . Hence, the assumption of continuum flow holds for liquid flow and the conventional theories are valid in describing the fluid flow and heat transfer characteristics. Herwig and Hausner [10] reported that flows in channels having a hydraulic diameter (D_h) of $\approx 1 mm$ are definitely considered continuum flows described by the Navier-Stokes equations, if the fluid is Newtonian. Hetsroni and Mosyak [11] also stated that in liquid flow and channels with hydraulic diameter between $1 \mu m \leq D_h \leq 1 mm$, the Kn is much less than unity. In addition, Qu and Mudawar [12] confirmed that the conventional Navier-Stokes and energy equations would be sufficient for predicting the fluid flow and heat transfer characteristics at a micro-scale channel.

Several papers have been devoted to analyzing the effects of the thermo-physical property variations with fluid temperature. The main outcome of these studies shows that it

is essential to take into account the variation of the fluid thermal conductivity and viscosity in the investigation of conventional [13-14] and narrow channel flows [15-16], especially at low Reynolds numbers. On the other hand, other properties, such as fluid density and specific heat, can be considered independent on temperature.

However, the performance of the *MICHX* cannot be evaluated with the other microscale heat sinks that have already been investigated in the literature. The most of the previous studies focused on developing a solution for cooling of electronics by flowing a coolant through minichannels to remove heat from the microelectronic components. The present study considers a multiport slab serpentine *MICHX* to transfer heat from a liquid to a gas in a cross-flow orientation.

Studies on water and different types of gas as working fluids in minichannels are available in open literature. However, investigation on the behavior of motor oil flowing through cross-flow *MICHX* is virtually very rare. Hence, an extensive exploration is needed to be familiar with the heat transfer and fluid flow characteristics of motor oil inside minichannels.

The objective of current study is to conduct experiments and examine the collected data from the cross-flow *MICHX* system (motor oil-air) to obtain the following:

- Experimentally analyze the heat transfer characteristics (h , Nu) of motor oil in *MICHX*.
- Examine the proto-type heat exchanger performance. Overall thermal conductance (UA), heat exchanger effectiveness (ϵ), and Number of transfer units (NTU).
- Establish correlations among the heat transfer and fluid flow characteristics and other dimensionless numbers.
- Compare the experimental results with the findings of a low viscous fluid (Automatic Fluid Transmission) analyzed in the same *MICHX* test specimen.

In order to achieve the aforementioned objectives accomplished, experimental runs are conducted. A cross-flow multi-port serpentine *MICHX* with motor oil and air as working fluids are utilized. Both working fluids are in single phase conditions throughout all of the experiments. In the current study, concentration is only on the motor oil side and thus equations and correlations related to the liquid-side is presented and discussed.

2. EXPERIMENTAL SET-UP AND PROCEDURES

In order to conduct the heat transfer and fluid flow research, an experimental facility was designed and assembled. The details of the experimental facilities were presented by Quaiyum *et al.* [17]. A short description of the setup is presented here. The set up consists of three loops; working fluid, air (cooling fluid), and city water loops. The motor oil is considered as the main loop. The circulation of the working fluid is taken from a tank and driven by a gear

pump with a maximum flow rate of $1.1 \times 10^{-3} \text{ m}^3/\text{s}$. Unlike other types of pumps, the gear pump can provide a constant flow rate of liquid without taking into account the pressure drop that usually occurs across the minichannels [18].

The thermo-physical properties are discussed hereafter. The fluid then passes through an inline electric heater which is capable of providing up to 6 KW to maintain the inlet temperature to the *MICHX*. A programmed control panel is connected to the electric heater to adjust the required heating temperature. The temperature inside the electric heater is measured by a thermocouple. A 230 micron filter was placed between the outlet of the Pump and the inlet of the minichannel to prevent the small particles from entering the micro channel heat exchanger. After that, the oil is forced to flow through an air-cooled type heat exchanger in a cross-flow arrangement while air passes by through wavy fins side, and finally the motor oil is sent back to the reservoir.

Two resistance temperature detectors (*RTDs*) and two pressure transducers (*PTDs*) are fixed at the inlet and exit of the test section to measure the temperatures and the pressures, correspondingly. The readings of the thermocouples are recorded by *DAQ* and then used to get the temperatures at the *MICHX* slab surface, serpentine bends, air inlet, and outlet. Generally, this loop can be said to consist of major and minor components. Major components are the oil tank, gear pump, and electric heater. Minor components are flow management accessories, flow monitoring devices, and flow measurement instruments.

The air is circulated inside a closed thermal wind tunnel. The *MICHX* is set up inside a test chamber, which is located in the test section of the wind tunnel. The air crosses the heat exchanger through fins and extracts the heat from the working fluid. To measure the inlet and the outlet temperatures of the air, type-T thermocouples are installed in the test section. There are also 46 thermocouples placed and scattered on bends, manifolds, headers, and inlet and outlet pipes to determine the *MICHX* slab surface temperature. The flow of air is controlled by a blower with a maximum speed of 18 m/s. For measuring the air inlet and outlet pressures, a Flow Kinetics FKT series is used. The city water flows through tubes of a built-in heat exchanger in the wind tunnel. The purpose of this loop is to control and retain the inlet air temperature. A 16-bit NI Data Acquisition (*DAQ*) system is incorporated to monitor and record all the experimental data as well as the measurements.

Five different air inlet temperatures between the ranges of 20°C to 40°C are considered in this study. For each of these inlet temperatures, four air velocity steps between 6 m/s to 18 m/s are examined against a constant oil inlet temperature of 75°C and four different oil flow rates, which resulted $0.85 < Re_{oil} < 3.5$. The Reynolds number is based on the *MICHX* diameter which is equal to 1 mm. The details of the calibration curves as well as for the instruments' calibration are given in Khan and Fartaj [18].

3. THERMO-PHYSICAL PROPERTIES OF MOTOR OIL

The motor oil used in combustion engines has natural properties including viscosity (μ), density (ρ), thermal conductivity (k), and specific heat (C_p), as well concocted ones, which are added to improve the overall performance of the oil and make them suitable for intended applications. For most liquids, the density, thermal conductivity, and specific heat are nearly independent of temperature. Viscosity, however, markedly decreases with increasing temperature [19-20]. As a viscous fluid, some of the thermo-physical properties of motor oil significantly changed with the change of temperature. Even though density, specific heat and thermal conductivity affect thermal and flow distributions in the flow field, their contributions are not as much as of the viscosity [21]. The density and viscosity of motor oil used in the current study are measured in the laboratory [22]; whereas, specific heat and thermal conductivity are provided by the manufacturer [23]. Viscosity of motor oil decreases very significantly with increasing temperature compared to the other thermo-physical properties as shown in Figures 3.1,3.2,3.3,3.4. From these figures, it is obvious that the density, specific heat, and thermal conductivity of the working fluid change linearly with temperature; whereas, the viscosity follows a polynomial relationship.

Figure 3.5 represents the effect of temperature variation on the viscosities of three different automotive fluids; motor oil, automatic transmission fluid (ATF), and ethylene glycol. This figure shows how highly viscous the motor oil is compared with the ATF and ethylene glycol. At low temperature, the difference in viscosities for the three fluids is distinctive. However, the viscosity of the fluids becomes very close as the temperature increases.

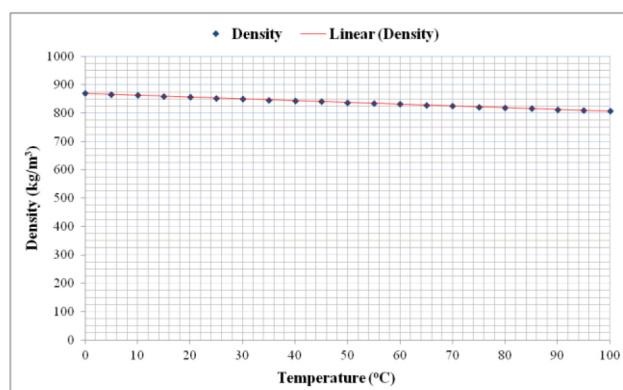


Figure 3.1. Effect of temperature on density of motor oil

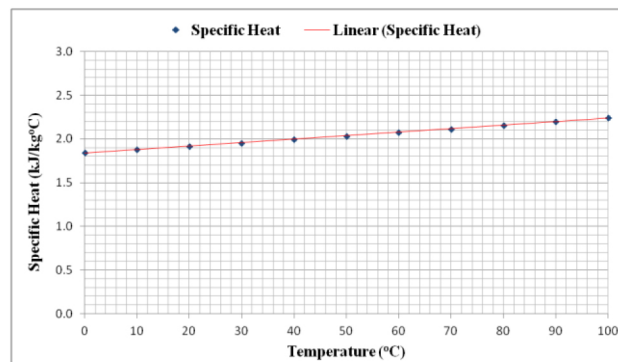


Figure 3.2. Effect of temperature on specific heat of motor oil

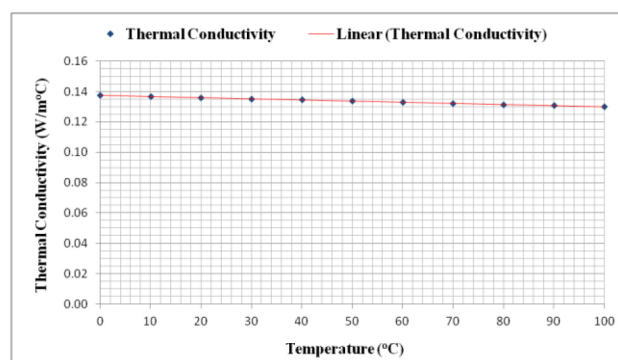


Figure 3.3. Effect of temperature on thermal conductivity of motor oil

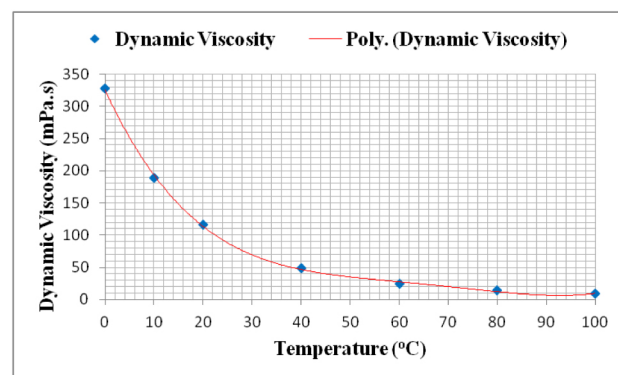


Figure 3.4. Effect of temperature on dynamic viscosity of motor oil