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A Methodology for Simultaneously Measuring Thermal Conductivity and Viscosity of Refrigerant Mixtures

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ABSTRACT

Properties, such as specific heat, viscosity, and thermal conductivity, are important thermophysical properties in any heat transfer study. Today, these properties are known for numerous fluids, however, there are still many fluids which have not been measured, especially those under the classification of refrigerant mixtures. This paper proposes a new approach for simultaneously measuring these properties. In this approach, thermal conductivity and specific heat are obtained by measuring the heat transfer charactertics of a heated test section, whereas viscosity is measured by a viscometer placed inline with the heated test section. A theoretical analysis and uncertainty analysis are also presented. The accuracy of the viscosity and thermal conductivity measurements was shown to be dependent upon the uncertainty of the equipment and heat transfer measurements.

NOMENCLATURE

A_i	inside tube heat transfer surface area, m^2
A_o	outer insulation surface area, m^2
a,b	exponential power constant for correlation curve fitting
a^e,b^e	exponential power constant for measured data curve fitting
C	coefficient of correlation curve fitting
C^e	coefficient of measured data curve fitting
CF	calibration function
C_p	specific heat, $kJ/kg \cdot K$
D	inside tube diameter, m
f	friction factor
$\bar{h}$	in-tube average heat transfer coefficient, $W/m^2 \cdot K$
$\bar{h}_o$	outer heat loss average heat transfer coefficient, $W/m^2 \cdot K$
k	thermal conductivity, $W/m \cdot K$
L	tube length, m
$\dot{m}$	mass flow rate, kg/s
$\bar{Nu}_D$	average Nusselt number based on diameter D
Pr	Prandtl number
$\dot{q}$	heat rate, W
$\dot{q}_{net}$	net heat input, W
$\dot{q}_{loss}$	heat loss, W
$\dot{q}_{tot}$	total heat input, W
q''	heat flux, W/m^2
Re_D	Reynolds number
$\bar{T}_i$	average inlet temperature of the test section, $°C$
$\bar{T}_o$	average outlet temperature of the test section, $°C$
$\bar{T}_w$	average wall temperature of the test section, $°C$
$\bar{T}_f$	average fluid temperature in the test section, $°C$
$\bar{T}_s$	average outer insulation surface temperature, $°C$
$\bar{T}_\infty$	average ambient temperature, $°C$
ΔT_{wf}	average temperature difference between $\bar{T}_w$ and $\bar{T}_f$, $°C$
Ur_{dk}	uncertainty percentage of k by the Dittus-Boelter correlation
Ur_{pk}	uncertainty percentage of k by the Petukhov and Popov correlation
Ur_{gk}	uncertainty percentage of k by the Gnielinski correlation
V	velocity, m/s
ρ	density, kg/m^3
μ	viscosity, $kg/m \cdot s$

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INTRODUCTION

Recently, researchers and scientists have been aggressive in searching for refrigerant alternatives because of the CFC problem. New pure refrigerants and refrigerant mixtures are two possible alternatives. The determination of thermodynamic and transport properties is a very important task in any refrigerant alternative evaluation. Although these properties have been measured for many refrigerants, there is a great need for these properties for new pure refrigerants, refrigerant mixtures and blends, and refrigerant-lubricant mixtures.

Viscosity and thermal conductivity, are necessary properties in any heat transfer analysis of a refrigeration cycle. Because of limitations in predicting transport properties by using theory, experimental measurement is the only direct method of measuring these two properties. There are a number of ways to measure viscosity such as the capillary viscometer[1,2], the vibrating principle viscometer[3], and the torsional oscillation viscometer[4]. For thermal conductivity, the vertical coaxial cylinder method[5,6], the transient hot-wire method[7,8], and the transient hot-strip method[9] are the usual methods employed.

As can be seen from the above list of methods, each property is measured by using a method independent of the other property. In this paper, a noval approach is proposed for simultaneously measuring these properties. This approach uses an inline viscometer and a heat transfer test section to dynamically measure viscosity and thermal conductivity at the same time. Viscosity is measured by a torsional oscillation inline viscometer while thermal conductivity is measured from knowledge of single-phase heat transfer characteristics of a heated test section. Meanwhile, by placing a mass flow meter and densimeter in series with the viscometer and test section, density and specific heat can also be measured.

THEORY

Heat transfer characteristics are usually described by dimensionless groups such as Prandtl number and Reynolds number, etc., which are correlated with properties. In other words, properties are employed to describe heat transfer characteristics. However, reversing this process, properties can also be obtained from known heat transfer characteristics. The method for measuring thermal conductivity and specific heat proposed here is based on the latter idea. For these purposes, a circular tube test section was selected with a turbulent, single-phase fluid pumped through it, and forced convection in-tube heat transfer occuring at the wall.

In-tube Heat Transfer Measurement

For convection heat transfer inside a circular cross-sectional tube, the average heat transfer coefficient can be determined as follows

$$\bar{h} = \frac{\dot{q}_{net}}{A_i\left(\bar{T}_w - \bar{T}_f\right)} = \frac{\dot{q}_{net}}{A_i \Delta \bar{T}_{wf}} \tag{1}$$

The variables, $\bar{T}_w$ and $\bar{T}_f$, the average tube wall temperature and mean fluid temperature, respectively, can be obtained from experimental measurements. The remaining quantity is the net heat input to the test section, $\dot{q}_{net}$, can be calculated from an energy balance if the total heat input, $\dot{q}_{tot}$, and heat loss to the enviroment from the test section, $\dot{q}_{loss}$, are measured.

Once the heat transfer coefficient is found, thermal conductivity can be determined from the definition of the Nusselt number as $\bar{h}D/\bar{N}u_D$. The Nusselt number can be obtained by using accurate theoretical or semi-empirical equations. For example, the Nusselt number, $\bar{N}u_D$, for a single-phase in-tube heat transfer has been found by a number of past studies to be correlated with Prandtl number, Reynolds number, and friction factor. A number of Nusselt number correlations have been published for this situation, with examples being the Dittus-Boelter correlation[10,11], the Petukhov and Popov correlation[11], and the Gnielinski correlation[10,11,12]. These three correlations are given below:

The Dittus-Boelter correlation(for heating),

$$\bar{N}u_D = 0.023 Re_D^{0.8} Pr^{0.4} \tag{2}$$

The Petukhov and Popov correlation,

$$\bar{N}u_D = \frac{(f/8)\, Re_D Pr}{1.07 + 12.7\,(f/8)^{1/2}\left(Pr^{2/3} - 1\right)} \tag{3}$$

The Gnielinkski correlation,

$$\bar{N}u_D = \frac{(f/8)\,(Re_D - 1000)\, Pr}{1 + 12.7\,(f/8)^{1/2}\left(Pr^{2/3} - 1\right)} \tag{4}$$

The friction factor, f, in the Petukhov and Popov correlation for a smooth tube is

$$f = (1.82 log_{10} Re_D - 1.64)^{-2} \tag{5}$$

while f in the Gnielinski correlation for a smooth tube is

$$f = (0.79 ln Re_D - 1.64)^{-2} \tag{6}$$

In the above equations, Re_D is defined as $\rho VD/\mu$ or $4\dot{m}/\pi D\mu$ and Pr is defined as $\mu C_p/k$.

As mentioned previously, with $\bar{h}$ and $\dot{m}$ measured, thermal conductivity can be obtained from the equality of setting the Nusselt number, $\bar{h}D/k$, equal to correlations given in Equations 2, 3, or 4. It should be noted that viscosity, μ, appears in both the Reynolds number and the Prandtl number and as such an accurate measurement of it from the in-line viscometer is essential.

Heat Loss Measurement

The purpose of measuring heat loss from the test section, $\dot{q}_{loss}$, is to obtain the net heat input to the test section, $\dot{q}_{net}$. The heat loss is transferred to the environment from the test section by natural convection. For calculating the heat loss, $\dot{q}_{loss}$, the following equation is used:

$$\dot{q}_{loss} = \bar{h}_o A_o (\bar{T}_s - \bar{T}_\infty) \tag{7}$$

where $\bar{T}_s$ and $\bar{T}_\infty$, the average outer insulation surface temperature and the average room temperature, respectively, can be obtained from experimental measurements. The natural convection heat transfer coefficient of the test section, $\bar{h}_o$, can be determined and calibrated from experimental measurements by using fluids with known specific heats.

Specific Heat Calculation

The specific heat for new fluids can be determined from an energy balance on the test tube, resulting in

$$C_p = \frac{\dot{q}_{net}}{\dot{m}(\bar{T}_o - \bar{T}_i)} \tag{8}$$

where $\bar{T}_i$ and $\bar{T}_o$ are the mean inlet and outlet temperature, respectively, while $\dot{m}$ is mass flow rate. This specific heat measurement is important when nonideal mixing occurs, which is the case for any refrigerant mixture and blend and for any refrigerant-lubricant mixture. In both cases, theoretical calculations of C_p from the pure fluids(either the pure refrigerant or pure lubricant) will not result in an accurate specific heat calculation.

NUSSELT NUMBER CALIBRATIONS

To obtain an accurate thermal conductivity, an accurate Nusselt number correlation is required. Although some published Nusselt number correlations have been shown to be accurate for in-tube heat transfer in circular tubes, calibrations from heat transfer data for the particular test section used in this study are still needed to improve further upon their accuracy. Therefore, calibrations were performed to improve upon the accuracy of the three Nusselt number correlations mentioned earlier.

Calibration Function

The method used for calibrating the Nusselt number correlations for the test tube used in this study is based on assuming that a calibration function exists between the values of the Nusselt number calculated from correlations and those calculated from experimental data taken on the test section. The calibration function is referred to as CF and it is defined as

$$CF = \frac{\bar{Nu}_{D_{experiment}}}{\bar{Nu}_{D_{correlation}}} = f(Pr, Re_D) \tag{9}$$

With this assumption, a set of CF values can be obtained from the Nusselt number ratios calculated from experimental data and from the correlations for different fluids. CF correlations can then be obtained by curve fitting with Pr and Re_D. The mathematical procedures are described below.

For in-tube heat transfer in this study, the following curve fitting equations are used for experimentally measured Nusselt number, $\bar{Nu}_D^e$, and correlation Nusselt number, $\bar{Nu}_D^c$, respectively.

$$\bar{Nu}_D^e = C^e Re_D^{a^e} Pr^{b^e} \tag{10}$$

$$\bar{Nu}^c_D = C Re^a_D Pr^b \tag{11}$$

Note that the superscript, e, denotes curve fitting equations obtained from measured data while the superscript, c, denotes curve fitting equations obtained from correlations. It should be also noted that the Dittus-Boelter equation is already in this form. By dividing Equation 10 by Equation 11, CF can be expressed as

$$CF = \frac{C^e}{C} Re^{a^e - a} Pr^{b^e - b} \tag{12}$$

THERMAL CONDUCTIVITY CALCULATIONS

Once the calibration function, CF, is obtained as a function of Re_D and Pr then Equations 9 and 12 can be combined and rearranged to determine thermal conductivity as follows.

$$k = \left[CF\left(Pr, Re_D\right)\left(\bar{Nu}_{D_{correlation}}\right)\right]^{-1} \bar{h}^e D \tag{13}$$

where $\bar{h}^e$ denotes the average heat transfer coefficient as experimentally measured.

For each of the three calibrated Nusselt number correlations, a thermal conductivity equation is obtained in a different form. The final equation for each correlation is presented below. It is important to note that the Prandtl number used in each theoretical correlation still has a thermal conductivity, k, in it and, as such, each of the three correlations handles this problem differently.

The Dittus-Boelter Correlation

The resulting equation for k from the Dittus-Boelter equation is

$$k_d = \left[\frac{\bar{h}^e D}{C^e Re_D{}^{a^e} \left(\mu C_p\right)^{b^e}}\right]^{\frac{1}{1-b^e}} \tag{14}$$

The Petukhov and Popov Correlation

The resulting equation for Pr from the Petukhov and Popov equation is

$$Pr^{2/3} - \frac{C^e \left(f/8\right)^{1/2} Re_D^{a^e - a + 1} \mu C_p}{12.7 C \bar{h}^e D} Pr^{b^e - b} + \frac{1.07}{12.7 \left(f/8\right)^{1/2}} - 1 = 0 \tag{15}$$

However, since k is implicit in Pr, k must be solved for by solving Pr first from the above equation. In other words, k is divided into μC_p to obtain Pr which is then treated as the unknown in the above equation. This equation is not an explicit linear type equation, but it can be solved by numerical iteration techniques such as the Newton-Raphson method. Once Pr is determined, the thermal conductivity, k, can be obtained from $\mu C_p / Pr$.

The Gnielinski Correlation

The resulting Pr number equation from the Gnielinski equation is

$$Pr^{2/3} - \frac{C^e \left(f/8\right)^{1/2} Re_D^{a^e - a} \left(Re_D - 1000\right) \mu C_p}{12.7 C \bar{h}^e D} Pr^{b^e - b} + \frac{1}{12.7 \left(f/8\right)^{1/2}} - 1 = 0 \tag{16}$$

As before, the k must be solved implicitly and Pr in this equation must be determined by numerical iteration methods.

VISCOSITY MEASUREMENT

A torsional oscillation in-line viscometer is used for viscosity measurements in this study. This type of viscometer uses the principle of "surface load": a vibrating surface in contact with a liquid experiences a force which is a function of the viscosity[4]. This viscometer placed in-line at the inlet portion of the test tube can dynamically measure the viscosity at the same time with the other measurements. The viscosity of this measurement can vary from a low viscosity range of 0.1 cp to a high viscosity range of 500 cp, which covers most of the pure refrigerants, refrigerant mixtures, and even refrigerant-lubricant mixtures with low lubricant concentrations.

UNCERTAINTY ANALYSIS

Based on the sensor and geometry related uncertainties of the measured data, used to determine thermal conductivity, the uncertainties in k calculated from the three different correlations can be determined. Therefore, the uncertainty analysis for various ranges of Pr and Re_D was performed. Sensor and geometry uncertainties are listed in Table 1.

Table 1: Sensor and geomtry uncertainty

sources	uncertainty
length, L	0.1 mm
diameter, D	0.1 mm
mass flow rate, $\dot{m}$	0.15% in kg/s
temperature, T_i, T_o, T_w	$0.05°C$
viscosity, μ	2.0%
specific heat, C_p	2.0%

Table 2 shows the uncertainty, presented as the percentage of measured thermal conductivity, by this proposed method for the three Nusselt number correlations. The uncertainty analysis was based on the sensor and geometry uncertainties listed in Table 1 at the operating conditions listed at the bottom of Table 2. The uncertainty varies with not only the correlation used but also with Re_D and Pr.

Table 2: Thermal conductivity uncertainty percentage by three Nusselt number correlations

case	Re_D	Pr	$Ur_{dk}\%$	$Ur_{pk}\%$	$Ur_{gk}\%$
at higher Re_D	160000	1.0	8.3	13.3	11.7
	160000	6.0	7.1	6.5	6.3
	160000	11.0	6.9	5.8	5.6
	160000	16.0	6.9	5.5	5.4
at middle Re_D	80000	1.0	7.3	10.3	9.1
	80000	6.0	6.8	6.0	5.8
	80000	11.0	6.8	5.5	5.4
	80000	16.0	6.8	5.2	5.2
at lower Re_D	10000	1.0	6.7	6.4	6.3
	10000	6.0	6.7	5.1	5.2
	10000	11.0	6.7	4.9	5.1
	10000	16.0	6.7	4.8	5.0
operating conditions:					
viscosity, μ :	$2.0 \cdot 10^{-4} Pa \cdot s$				
specific heat, C_p :	$1.0\ kJ/kg \cdot K$				
inlet temperature, T_i :	$10°C$				
heat input rate, $\dot{q}$:	1 kW				

From the uncertainty analysis, the following observations can be made:

1. Lower the Pr and higher the Re_D, then the larger the uncertainty. However, the uncertainty of k from the Dittus-Boelter correlation seems to be less affected by Re_D than the other two correlations.
2. At the middle range of Re_D, Pr also significantly affects the k uncertainty for the Petukhov and Popov correlation and the Gnielinski correlation as it at higher Re_D cases.
3. At the lower range of Re_D, the k uncertainties from all three correlations are around 6 percent no matter how the Pr changes.

The uncertainty of CF is based on the two Nusselt numbers ratios as defined in Equation 12, therefore, the only uncertainty source of CF is from the Nusselt number curve fittings. This uncertainty will be dependent on what the curve fitting method used and how the data fits.

FUTURE EXPERIMENTAL PLANS

Prior to using the above methodology for measuring thermal conductivity, an accurate CF must be calibrated and obtained from experimental data taken on a number of fluids with known properties. In a recent ongoing study, several refrigerants were selected as basic fluids for CF calibration purposes. The fluids are R-22, R-12, R-113, R-114, and ethylene glycol-water mixtures. The fluids with unknown properties to be investigated include new pure refrigerants and refrigerant mixtures, such as R-236ea and any of several blends and mixtures classified as substitutions for R-22. Many of these blends and mixtures are made of varying concentrations of R-32, R-125, and R-134a. The results of these measurements will be presented in the near future.

CONCLUSIONS

This paper proposes a noval approach for simultaneously measuring several transport and thermodynamic properties, such as thermal conductivity, viscosity, specific heat, and density. This approach uses single-phase in-tube heat transfer knowledge to obtain thermal conductivity whereas viscosity is measured by a viscometer placed in-line with the heat transfer test section. The methodology and an uncertainty analysis are presented in this paper. The determination of a calibration function, CF, by experiments using fluids with known properties, is shown to be important for accurate thermal conductivity measurements. Three different Nusselt number correlations used for calculating thermal conductivity in this study are also examined. The uncertainty analysis shows that the accuracy of k can be measured within 6 percent over a range of Prandtl number.

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