Heat Transfer to Viscous Solutions

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Abstract

The focus of this study is on heat transfer to solutions with viscosities greater than those commonly encountered. An experimental facility was built to measure convective heat transfer coefficients for fluids with viscosities ranging up to 1,000 cP. Results for both single-phase (liquid) and two-phase (liquid and vapor) heat transfer are presented, for aqueous solutions of polyethylene glycol. Initial indications are that single-phase coefficients are reasonably well predicted by standard correlations, but two-phase coefficients are notably different than those correlated for non-viscous fluids.

Introduction

In two important process industries, namely food processing and polymer processing, fluids of high viscosities are often encountered [1]. Design of heat exchangers for such applications are often hampered by lack of published data or correlations, since the standard engineering models were predominantly based on data for common fluids (e.g. water and refrigerants) with viscosities of 1-10 cP and Prandtl numbers of 1-100 [2]. While one may expect that single-phase correlations may be extrapolated over wide ranges with fair confidence, there is no such assurance for two-phase correlations. The very nonlinear behavior of two-phase flows, especially where there is evaporative phase change, argues against extrapolation of existing correlations and models over orders of magnitude in viscosities and Prandtl numbers [3]. The objective of this experimental investigation was to measure convective heat transfer coefficients for viscous solutions, for both single-phase and two-phase flows.

Experiment

Figure 1 is a diagram of the experimental facility, showing the flow loop and details of the instrumented test section. Subcooled liquid solution flows from a surge tank and is further sub-cooled before entering a gear pump. The liquid exiting the pump is preheated to specified temperature before introduction to the test section. The solution then proceeds through the test section where it is heated in either single-phase convection or evaporated in two-phase convection. A double-pipe heat exchanger and a water-cooled condenser removes the added thermal energy, returning the test fluid to its initial enthalpy for recycle to the test section. In order to minimize dissolved gases in the test fluid, degassing is accomplished by pulling a vacuum throught a knockback condenser located above the main condenser.

The pressure and temperature of the process fluid are measured directly before and after the fluid enters the test section. The solution temperatures are measured using 1/16” diameter K-type thermocouples. Pressure is measured using Validyne dp-15 pressure transducers. Flow is measured before the test section using a Flocat positive displacement flow meter. K-Type wall thermocouples are evenly spaced 3 inches apart along the ½” diameter, 6 feet long test section. Electrical bus bars attach a power supply to each end of the test section providing resistive heating to the test section. The outlet temperature and pressure are measured directly after the test section. A sight glass at the outlet allows the observation of flow patterns. Data are collected, analyzed, and organized in real-time using an AMUX-64T multiplexer and a 16 channel, 16 bit DAQ card using Labview.

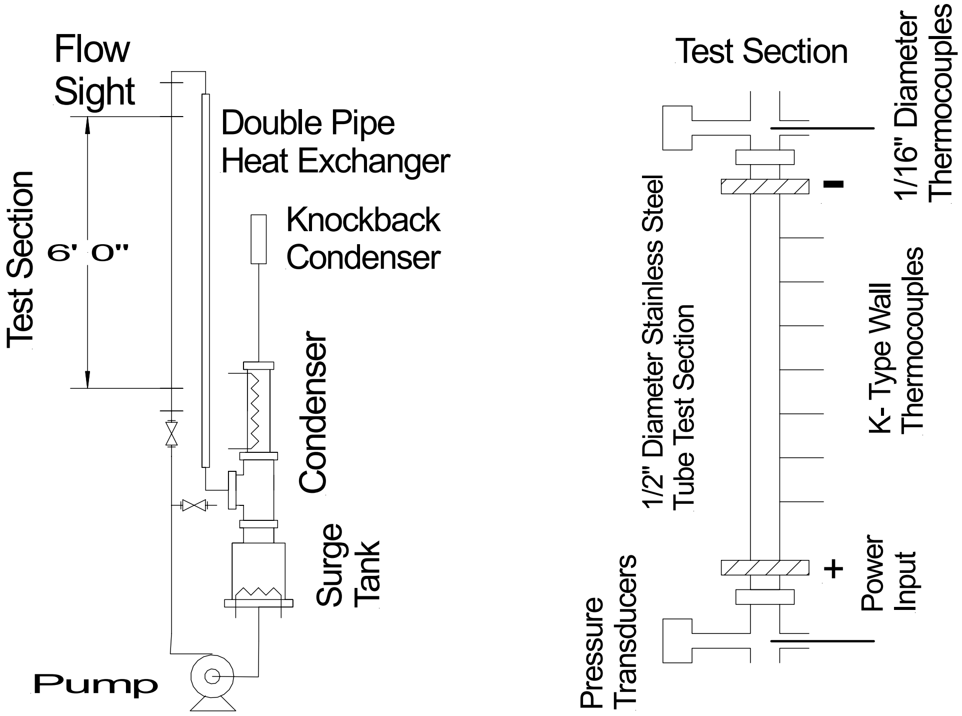

Figure 1
Test loop and test section

Results

As a qualifying run, measurements were initially obtained for the heating of single phase water and plotted as Nusselt number versus Reynolds number (see Figure 2). Since the Reynolds numbers for these data ranged from 3,000 to 9,500, it is appropriate to compare the measured values to the Petukov(1) and Gnielinski(2) correlations in the laminar-turbulent transition region [4].

$$Nu = \frac{f/8 \operatorname{Re} \Pr}{1.07 + 12.7(f/8)^{1/2}(\Pr^{2/3} - 1)} \qquad 10^4 < \operatorname{Re} < 5 \cdot 10^6 \ , 0.5 < \Pr < 2000 \quad (1)$$

$$Nu = \frac{f/8 (\operatorname{Re} - 1000)\Pr}{1 + 12.7(f/8)^{1/2}(\Pr^{2/3} - 1)} \qquad 3000 < \operatorname{Re} < 5 \cdot 10^6 \ , 0.5 < \Pr < 2000 \ (2)$$

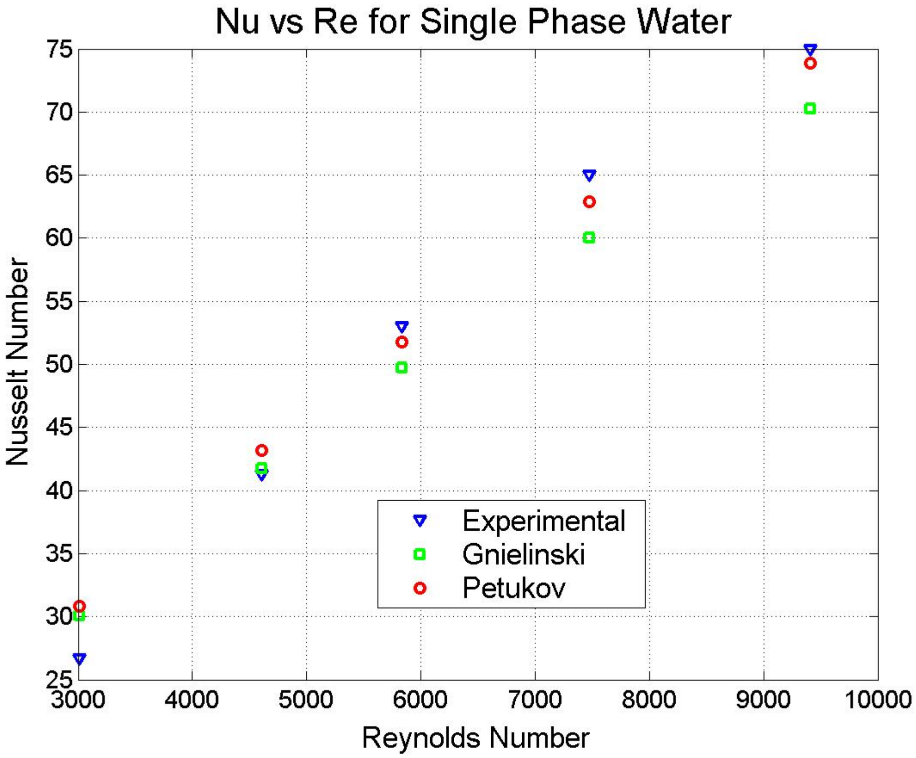

Figure 2
Qualifying data obtained with water

It is seen that agreement between experiment and correlations was good for these data, lending confidence to the ability of the loop to produce valid data.

Figure 3 is an axial plot of the local Nusselt number for single phase laminar flow of polyethelene (PEG) solution of 0.6 weight fraction with a Reynolds number <15 for the entire length of tube. Due to the low velocities and laminar nature of the vertical flow, both forced and natural convection have appreciable effect on the overall heat transfer. Two correlations, by El-Genk and Rao (3&4), are appropriate for this regime since they account for the combined effects of natural and forced convection [5].

$$Nu = 1.86 Gz^{.33} \left(\frac{\mu_B}{\mu_W} \right)^{.14} \qquad 125 < \operatorname{Re} < 800, \ 10^5 < Ra < 1.6 \cdot 10^6 \qquad (3)$$

$$Nu = 4.75Gz^{.15} \qquad 125 < \mathrm{Re} < 800,\ 10^5 < Ra < 1.6 \cdot 10^6 \qquad (4)$$

The axial variation of Nusselt number predicted by these correlations are compared to the experimental measurements in Figure 3. It should be noted that both correlations work to within 10% for 125<Re<800. The correlation with the viscosity ratio seems to work better at the entrance while the correlation without it works better as the flow becomes more developed.

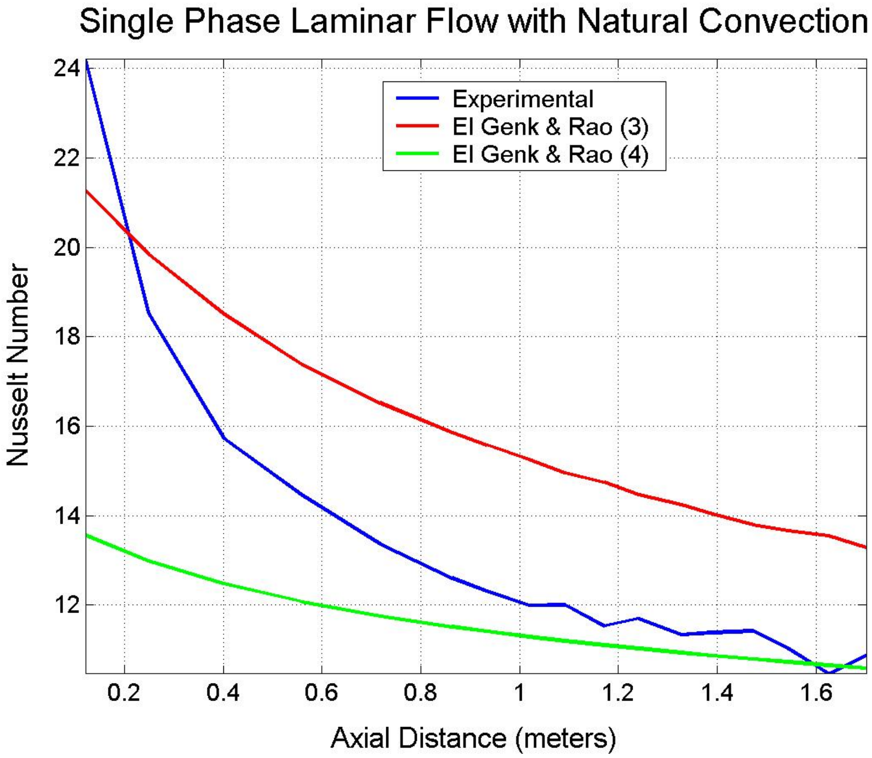

Figure 3

Single-phase convection for PEG solution

Two-phase evaporative heat transfer data were obtained for PEG solutions of moderate viscosities in the range of 15-50 cP, with heat fluxes of 5-85 kw/m^2, vapor qualities up to 0.2, and mass fluxes in the range of 40-200 kg/m^{2}s. Figure 4 displays a typical axial temperature plot showing the different regimes encountered during a two-phase boiling run. The fluid starts as sub-cooled liquid and first undergoes single phase convective heat transfer. As the fluid gains sensible heat and increases in bulk temperature, the wall temperature goes up accordingly. Eventually a point is reached where the wall is sufficiently superheated above the fluid saturation temperature to initiate sub-cooled boiling. With the increase in heat transfer coefficient associated with subcooled boiling, the wall temperature decreases and drops to a level corresponding to the driving temperature difference required to sustain two-phase heat transfer at the given heat flux. Subcooled boiling continues until the fluid's bulk enthalpy reaches saturation state. Thereafter, net evaporation occurs with saturated convective boiling [6].

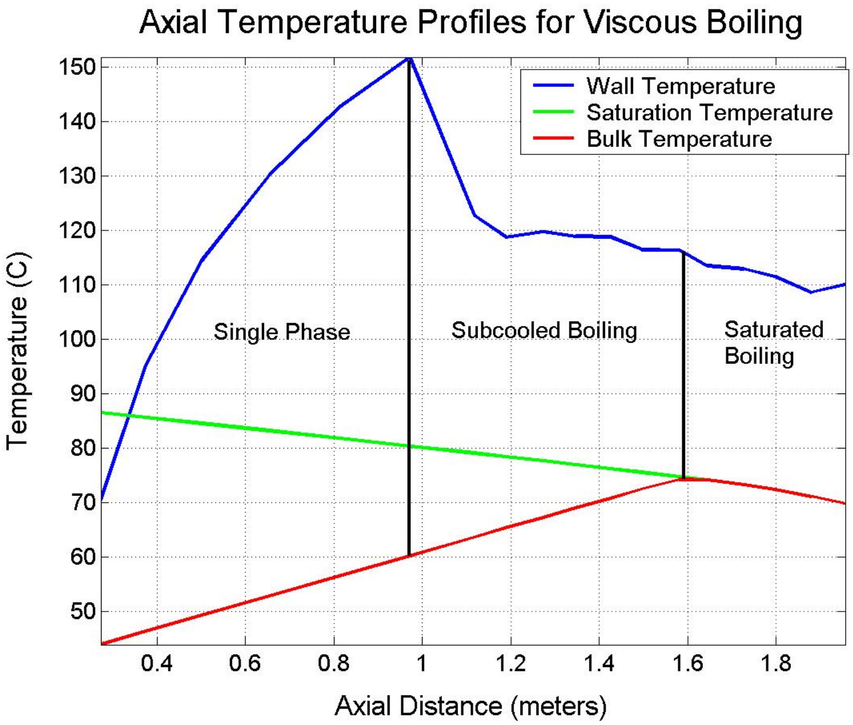

Figure 4
Axial temperature profiles for two-phase heat transfer
to PEG solutions

As compared to typical non-viscous two-phase evaporative flow plots, there are already some interesting points to note. Usually a typical value for the wall superheat, ΔTsat, is on the order of 5-10˚C. As indicated in Figure 4, superheat magnitudes for the PEG solutions have been observed to exceed 50˚C, much larger than expected at the test heat fluxes. Secondly, the usual increase in heat transfer coefficient with increasing vapor quality (as solvent evaporates) is not observed for the PEG solution. This is indicated by the fairly constant wall superheat as the fluid progresses from subcooled to saturated boiling.

The above observations lead to the tentative conclusion that two-phase, evaporative heat transfer coefficients may be noticeably lower for viscous solutions than those for ordinary fluids at corresponding heat fluxes. This preliminary conclusion is indicated by the results shown in Figure 5, which indicate that the experimentally measure two-phase coefficients for the viscous PEG solutions are overpredicted by the standard correlations of Chen [7] and Bennett & Chen [8], by more than 50%. Between the two correlation, the Bennett-Chen correlation does give better agreement with measurements, due to its accounting for mass transfer resistance in the solution.

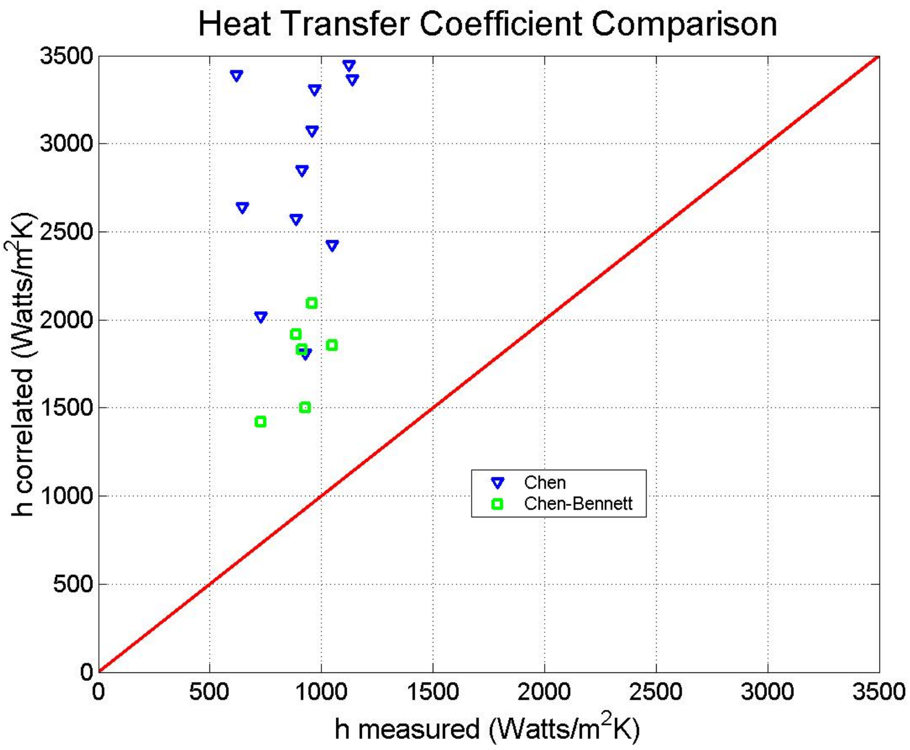

Figure 5
Boiling heat transfer coefficients for PEG solution,
compared to standard correlations for ordinary fluids

Conclusion

Experimental measurements of convective heat transfer to PEG solutions indicate that single-phase behavior for these moderately viscous fluids is similar to that for common, low-viscosity fluids. However, the data indicate that two-phase, boiling heat transfer coefficients for the viscous solutions are noticeably lower than those for lower-viscosity liquids.

Nomenclature

f	Darcy Moody friction factor
Gz	Graetz number
h	Heat transfer coefficient, $W/m^2\ K$
Nu	Nusselt number
$\Pr$	Prandtl number
Re	Reynolds number

μ_B	Viscosity evaluated at the mean bulk temperature, $kg/m \cdot s$
μ_W	Viscosity evaluated at the wall temperature, $kg/m \cdot s$

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