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Neutron imaging of diabatic two-phase flows relevant to air conditioning

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Abstract

The design of the evaporator of an air conditioning system relies heavily on heat transfer coefficients and pressure drop correlations that predominantly involve an estimate of the changing void fraction and the underlying two-phase flow regime. These correlations dictate whether the resulting heat exchanger is oversized or not and the amount of refrigerant charge necessary to operate. The latter is particularly important when dealing with flammable or high GWP refrigerants.

Traditional techniques to measure the void fraction and visualize the flow are either invasive to the flow or occur downstream of the evaporator, where some of the flow distribution will have changed. Neutron imaging has the potential to visualize two-phase flow in-situ where an aluminium heat exchanger structure becomes essentially transparent to the penetrating neutrons. The subatomic particles are attenuated by the passing refrigerant flow. The resulting image may be directly related to the void fraction and the overall picture provides a clear insight into the flow regime present.

This work presents neutron images of the refrigerant Isopentane as it passes through the flow channels of an aluminium evaporator at flowrates relevant to air conditioning. The flow in a 4mm square macro channel is compared to that in a 250μm by 750μm rectangular microchannel in terms of void fraction and regime. All neutron imaging experiments were conducted at the High Flux Isotope Reactor, an Oak Ridge National Laboratory facility.†

1. Introduction

Microchannel heat exchangers have a distinct advantage of much higher surface areas in comparison to conventional larger scale units. Boiling refrigerants in microchannels offers a cooling capacity that can match the heat output from power electronics. Air conditioning and refrigeration systems are taking advantage of this technology with aluminum microchannel evaporators becoming more widespread.

Performance prediction from a microchannel evaporator is still an issue, however, with correlations developed for large diameter heat exchangers providing little success at smaller scales. Void fraction is one of the most important parameters used in characterizing and modeling both diabatic and adiabatic flows. In the latter, circular glass tubes are employed and image processing of the resulting high speed videography provides an estimate of the void fraction. In the case of the former, open heat exchanger channels are enclosed by a transparent top to

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allow the visualization to occur, while acknowledging the obvious effects on the heat transfer and fluid flow boundary conditions.

Passing neutrons interact in general with the nucleus of the sample material. This interaction leads to a scattering or attenuation on the neutrons so that a scintillator downstream of the scintillator will capture a fraction of the neutrons.

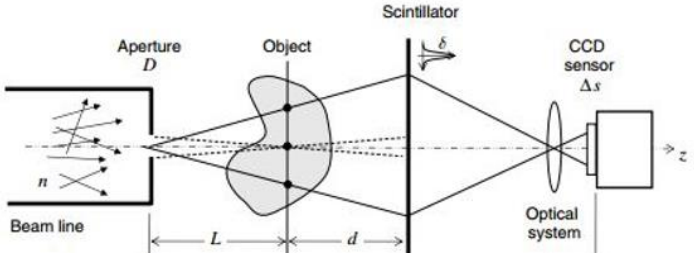


Fig. 1. Schematic layout of a neutron imaging facility [1]

Due to the exponential nature of the attenuation, the individual thicknesses of each material making up the sample may be added to each other. Thus $t = \sum_{i=1}^{N} t_i$ where t_i is the thickness of each layer of material. The attenuation through the empty microchannel heat exchanger is given by

$$I_m = I_o e^{-\mu_m t_m} \tag{1}$$

I_0 refers to the open beam intensity, μ_m is the Aluminum attenuation coefficient, t_m is the metal thickness and I_m is the image intensity. In the case of the heat exchanger full of liquid refrigerant, the attenuation becomes

$$I_{fm} = I_o e^{-\mu_m t_m - \mu_r t_f} \tag{2}$$

The Dividing equation (2) by (1) gives

$$I_{fm}/I_m = e^{-\mu_r t_f} \tag{3a}$$

or

$$t_f = -\frac{1}{\mu_r} \ln\left(I_{fm}/I_m\right) \tag{3b}$$

Similarly, for channels containing two phases and assuming the vapor phase density is so low it does not attenuate the neutron beam

$$t_r = -\frac{1}{\mu_r} \ln\left(I_{rm}/I_m\right) \tag{4}$$

Then the local chordal void fraction becomes

$$\varepsilon = \frac{\ln(I_{rm}) - \ln(I_m)}{\ln(I_{fm}) - ln(I_m)} \tag{5}$$

Thus in taking this approach, it is necessary to capture images of the heat exchanger empty of and completely full of liquid refrigerant. Alternatively, a calibration of the neutron transmission through varying thickness of refrigerant may be pursued [1]. In an ideal scenario, the distances L and d would be infinite to allow only truly straight neutrons to interrogate the sample and only those that transmit to strike the scintillator but in reality the more the sample is removed from the aperture, the lower the neutron flux and the further the sample is from the scintillator, the more the image resolution suffers. Available beamline space generally dictates these distances.

Nomenclature

d	distance from sample to scintillator	(m)
I	intensity	(-)
L	distance from aperture to sample	(m)
t	material thickness	(m)
Subscripts		
f	full of liquid refrigerant	
m	metal	
o	open beam	
r	refrigerant	
Symbols		
ε	chordal void fraction	(-)
μ	attenuation coefficient	(m^{-1})

2. Methods

The portable flow loop as described in Geoghegan and Sharma (2015) [2] was employed in this work. Some minor modifications include the addition of a four-way valve to allow different test sections to be tested without the need to remove the charge as well as the use of a differential pressure transducer across the test section. The transparent upstream visualization section was removed and the downstream version was replaced by a standard HVAC sight glass. This alteration removed the safety concerns that the plastic visualization sections could withstand the high temperatures associated with a critical heat flux phenomenon while still allowing a visual confirmation of the phase nature of the flow.

The imaging experiments were conducted at the CG1-D Cold Neutron Imaging Facility. The beam is polychromatic with a range in wavelengths from 0.8 to 6 Angstroms and a neutron flux on the order of 10^7 n $cm^{-2}s^{-1}$. The MCP detector was employed to image the microchannel flow. It has a 2.8 cm x 2.8 cm field of view and a highest spatial resolution of 55µm. Exposure times were fixed at 60s and each flow condition was imaged twice.

The microchannel test section was created using Ultrasonic Additive Manufacturing (UAM) where layers of metal from featureless aluminum foil stock are merged using sound. A 750µm mill created the fine features, in this case the flow channels. The test section was built on its side to create the 250 µm x 750µm channels. The heat exchanger was constructed of Aluminum and consists of 20 channels, 20 mm long, connecting to manifolds that lead to the 4 mm x 4 mm inlet and outlet. The stair-step design of the manifolds was necessary to avoid build overhang limitations of UAM process. Flanges were machined on either end to allow the use of quick release sanitary or vacuum clamps. This approach made threading into Aluminum unnecessary. The total length of the heat exchanger is 60 mm.

The heat to the test section was provided by 6 heating cartridges that were embedded in to the Aluminum stock. Each cartridge has a thermocouple embedded within it. These temperatures, together with temperatures and pressure across the flow loop, are monitored for possible excursions. The wall temperature of the test section was also measured in experiments conducted away from the neutron beam. It was thought that temperature measurements taken close to the beam are unreliable. The microchannel was held in a horizontal condition so that the captured neutron image appears to be a single channel but is in fact a stack of 20. The image is therefore an average of the flow condition in all 20 channels.

The images from the microchannel are compared to that from the macroscale 4mm square single channel as employed by Geoghegan and Sharma (2015) [2]. The latter was again fabricated from Aluminum 6061 and is 83.32 mm in length. In this case the detector consisted of a 50 µm thick LiF/ZnS scintillator and a DW936 IkonL ANDOR^{TM} charge coupled device (CCD) camera with a spatial resolution of 100 µm. The maximum field of view is 7 cm x 7 cm.

In order to avoid unnecessary neutron attenuation, the heated test section is exposed to ambient conditions. Thus heat loss due to natural convection is accounted for via the approaches of Hassani (1987) and Hassani and Hollands (both in 1989), as recommended by Rohsenow [4] for bodies with small aspect ratios.

The refrigerant Isopentane was selected as the refrigerant based on a successful calibration (Geoghegan et al., 2015) [2] and subsequent neuron imaging of a macroscale flow [3].

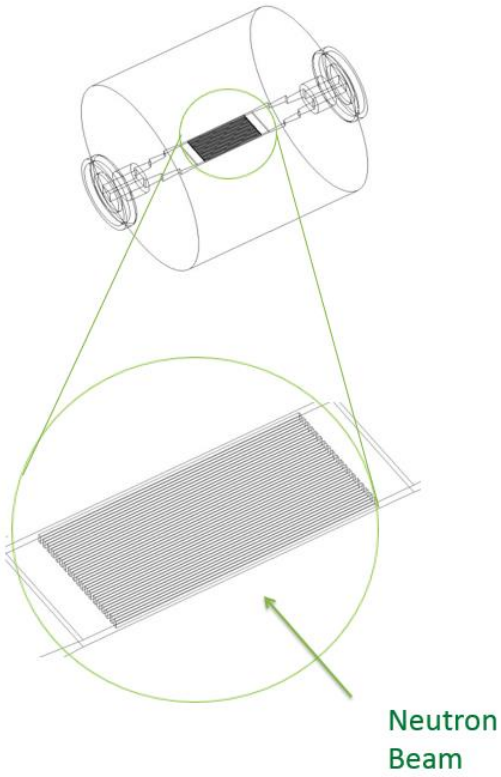


Fig. 2. Aluminum microchannel heat exchanger



Fig. 3. Aluminum microchannel heat exchanger with heating elements

3. Results and Discussion

Figure 4 is the raw neutron image of the microchannel heat exchanger full of liquid refrigerant. The image is a representation of an average across all channels in the stack. The darkened regions at the top and bottom is due to shuttering of the beam line aperture that eliminates irradiation of the heating elements. The scintillator consists of 4 plates that were used to center the microchannel but this does create a slight discontinuity in the image moving

across the plate borders. The width of each manifold is at least twice that of the summed with of the microchannels. The manifolds thus appear darker in the image because of the greater attenuation. The neutron image of the empty microchannel (Figure 5) shows a barely perceptible change in contrast through the channels, reiterating the transmission properties of Aluminum.

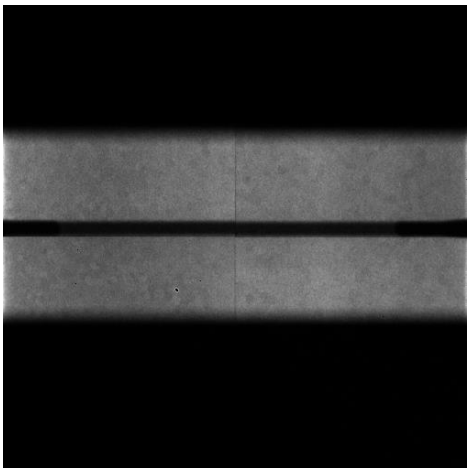


Fig. 4. Neutron image of the microchannel heat exchanger full of liquid refrigerant

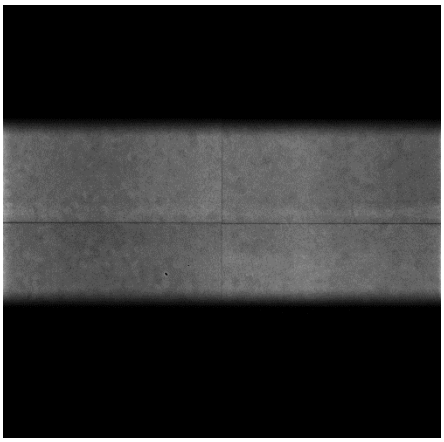


Fig. 5. Neutron image of the empty microchannel heat exchanger

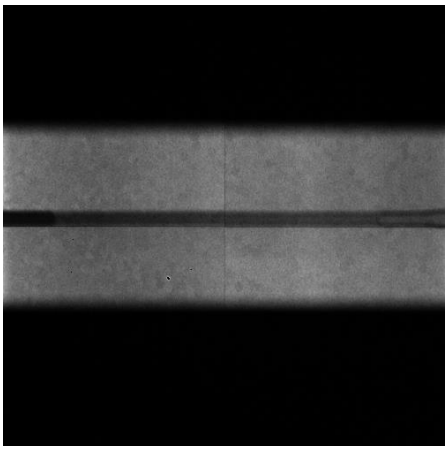


Fig. 6. Neutron image of the microchannel heat exchanger with a boiling flow

for a mass velocity of 768 kg/m^{2}s, a heat flux of 181 kW/m^2 and a 7 ^{o}C level of subcooling

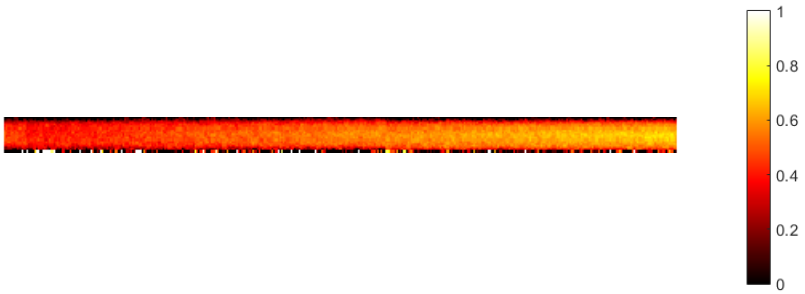


Fig. 7. Void fraction image associated with Figure 6

Figure 5 is the neutron image of a boiling flow of mass velocity of 768 kg/m^{2}s, a heat flux of 181 kW/m^2 and a 7 ^{o}C level of subcooling. The inlet manifold is obvious as the darkest portion of the image. A clear liquid meniscus separates the outlet manifold portion of the image from the channels. Qualitatively, the image through the channels suggests a symmetric liquid film of equal thickness on the top and bottom of the channels. Equation (5) transforms the neutron image in to a void fraction image and a color map is employed to aid the visualization. The void fraction profile is again more or less symmetric about the flow centerline. This suggests the flow is surface tension driven rather than gravity driven and thus the heat exchanger fits in to the classic definition of a microchannel that is surface tension dominant. In this flow condition boiling is already taking place in the manifold with a void fraction of 0.4 at the channel entrance. It may also be inferred that nucleate boiling is occurring in the entrance portion of the channels and elongated bubbles are forming as the flow progresses. A certain level of noise is present in the image. This is inherent to a neutron image where the distance d from the sample to the scintillator is finite and scattered neutrons are also captured in the image. The image analysis suggests the resolution captured is 55 µm, the highest resolution available. The sample was positioned a half a diameter of the round aluminum test section away from the scintillator to allow the natural convection to be unimpeded.

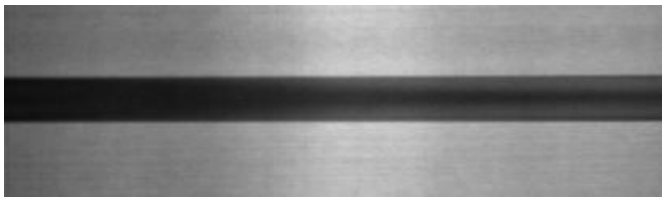


Fig. 8. Neutron image of the microchannel heat exchanger with a boiling flow
for a mass velocity of 783 kg/m^{2}s, a heat flux of 115 kW/m^2 and a 9 ^{o}C level of subcooling



Fig. 9. Void fraction image associated with Figure 8

It is instructive at this point to compare the images from the microchannel to that taken from the macrochannel for similar mass velocity and heat flux. Figure 8 is a neutron image of the 4 mm x 4 mm flow channel with a mass velocity of 783 kg/m^{2}s, a lower heat flux of 115 kW/m^2 and a 9 ºC level of subcooling. The resulting void fraction image (Figure 9) has a very different characteristic to the microchannel image. It is characterized by a liquid flow through the center of the channel with high void fractions on the top and bottom. High speed videography of this flow taken downstream of the heat exchanger revealed large bubbles in the upper portions of the flow channels while faster moving bubbles contributed to the void fraction in the bottom portion of the channel. This comparison illustrates the importance of channel scale to the void fraction profile and flow regime.

4. Conclusions and Future Work

Neutron imaging is a powerful tool that can aid many areas of research, including boiling two-phase flow. It reveals the void fraction within real operating heat exchangers without interfering with the flow. In this work, the void fractions for a particular flow condition are shown to be very different for macro and micro channel scales. Due to the aspect ratio of heat exchanger width to height (9.75 mm to 0.75 mm) the authors are aware that a slight tilt in the heat exchanger can distort the neutron image. Image analysis suggests the heat exchanger may have been tilted by 1.5º about the heat exchanger axis. The team are currently correcting the images by tomographic reconstruction.

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