Flow Visualization of R-134a in a Capillary Tube

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Abstract

This paper reports on a novel flow visualization study in which the two-phase flow behavior of R-134a in a small-bore capillary tube is viewed from inside of the tube using a fiberscope. All previous capillary tube flow visualization studies, some dating back nearly fifty years, have used glass tubes through which two-phase flow behavior was observed and photographed from the outside. Because glass tubes have extremely smooth inner walls in comparison to the relative roughness of a drawn copper capillary tube, the two-phase flow behavior may be different. The proper characterization of the two-phase flow field downstream of the flash point is necessary for an accurate prediction of pressure drop and flow rate in the capillary tube.

The fiberscope used was a 0.020 in. (0.51 mm) diameter glass fiber bundle roughly 39 in. (1 m) in length with at teflon coating. The fiberscope was inserted into the upstream end of the capillary tube through a specially designed fitting. The fiberscope lens at the end of the fiber bundle was positioned approximately 32 in. (80 cm) downstream of the capillary tube inlet. By carefully controlling the upstream pressure and temperature, the location of the onset of vaporization, or flash point, could be positioned near the fiberscope lens. In this way, the two-phase flow detail could be viewed in the region of the flash point. The flow visualization results presented herein clearly indicate that once the vaporization is initiated the two-phase flow appears to be plug/slug-like, in contrast to developing bubbly flow behavior reported for the glass tubes in previous studies.

Introduction and Background

The small-bore capillary tube is the most common expansion device used in household refrigerators and other small refrigeration systems. Refrigerant flow behavior in the capillary tube has been studied extensively for the past 50 years, and several of these studies have included a flow visualization component. In one of the first reports, Cooper et al. found that the location of the onset of vaporization, or flash point, would shift up and down the length of tube as subcooling was adjusted, as was predicted by theory. They described the two-phase flow region in a glass capillary tube as a fog-like, further saying that there was no obvious evidence of slug or bubble flow[1]. Mikol and Dudley performed a similar study. Using a high-speed flash device, they noted that the two-phase flow through a glass tube consisted of a stream of small bubbles that originated at or next to the tube wall. As the bubbles moved downstream, the bubble diameters grew while moving in towards the center of the capillary tube. Mikol and Dudley also noted that after vaporization was initiated at a definite wall location, it remained stable[2]. A later study by Koizumi and Yokoyama using a Pyrex glass capillary tube found that as the bubbles move away from the initial vaporization site, the bubbles are scattered in the refrigerant uniformly and discretely. Moving downstream, they state that vaporization transpired in all sections of the refrigerant. Finally, Koizumi and Yokoyama noted that near the exit of the capillary tube, the vaporization is more galvanized and that the flow is nearly homogeneous involving numerous bubbles[3]. Yana Motta et al. found that two-phase flow initiates at a specific location on the tube wall and has a fog-like appearance immediately downstream[4].

The common feature among these earlier flow visualization studies has been the glass capillary tube. Glass is known to have a very smooth surface. In fact, Munson et al. consider it to have a 0.0 roughness height[5]. Drawn copper tubing, in comparison, has a roughness height that averages 1.5 to 2.0 μm. Carter and Bittle studied the inner wall surface of drawn copper capillary tubes under a microscope and observed two different categories of roughness: longitudinal trenches and random obstructions that appeared as peaks or valleys. The roughness depth or height ranged between 0.5 and 2.5 μm. The inner surface of a much larger diameter drawn tube was similar to the surfaces of the capillary tubes, which indicated that the inner surface features are a result of the drawing process[6]. In comparison to the inner surface of glass tubes, the natural roughness of the drawn tubing wall provides a denser field of potential nucleation sites. As a result, the actual two-phase flow development in a drawn copper tube may be much different than what has been observed in a glass tube.

This paper reports on a flow visualization study in which the two-phase flow behavior of R-134a is viewed from the inside of a copper capillary tube using a 0.020 in. (0.51 mm) diameter flexible fiberscope. The flow field was viewed from upstream looking downstream, with the particular goal of viewing the onset of vaporization at the flash point and characterizing the specifics of the hydrodynamic behavior. The paper describes the techniques developed for using the fiberscope, and presents a series of recorded images of the two-phase flow. Conclusions regarding the observed two-phase flow behavior are compared to the results reported in previous studies.

Experimental Apparatus

Capillary Tube Test Stand

The TCU capillary tube test facility was designed and built to represent conditions of a household refrigerator at the capillary tube inlet and exit. A schematic of the existing facility is given in Figure 1[7]. A one-pass-through design concept is used that has several advantages when compared to a compressor driven system, including a faster time to reach steady conditions and better control of the capillary tube inlet pressure.

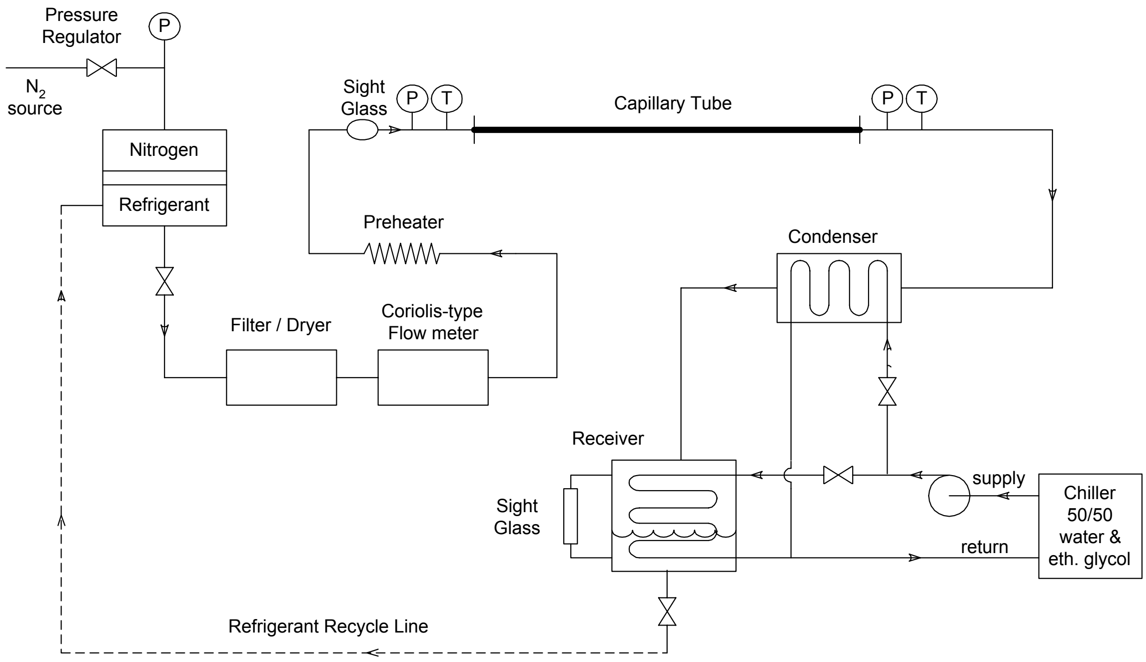

Figure 1. Capillary tube test facility schematic[7].

Capillary tube inlet pressure is controlled using a bladder accumulator, which allows the inlet pressure to be controlled to within ±0.25 psi (±1.7 kPa). The bladder accumulator effectively pushes the refrigerant down through the capillary tube at the controlled inlet pressure. The capillary tube exit pressure (representing the evaporator pressure) is established in the condenser and receiver. A two-phase condition always exists in the receiver when the system is charged with refrigerant. The operating temperature of the condenser and receiver (and thereby the capillary tube exit pressure) is controlled by using a temperature controlled water-glycol supply from a 3-ton chiller.

The capillary tube inlet temperature is established with an electric preheater. The preheater power level is controlled manually with a rheostat. The preheater consists of electric heating tape wrapped around an 8 ft (2.4 m) length of 3/8 in. (9.5 mm) copper tubing that has an enhanced inner surface. The preheater and the tubing connecting the capillary tube inlet are insulated to minimize heat loss. The capillary tube inlet temperature and pressure are measured 2.5 in. (6.4 cm) prior to the capillary tube inlet, which ensures a known inlet condition.

System temperatures are measured with type-T thermocouple probes immersed in the refrigerant flow stream at several key points in the system. Thermocouple measurement accuracy is ±0.5°F (±0.3°C). System pressures are measured with pressure transducers at the capillary tube inlet and exit. The accuracy of the pressure transducers was verified to be ±0.5 psia (±3.4 kPa). The mass flow rate though the capillary tube was measured prior to the preheater with a coriolis-type true mass flow meter, which is accurate to within 1%. The data acquisition is computer controlled using National Instruments LabVIEW®. During test facility operation, the data acquisition program runs continuously and provides a continuous visual update to the computer monitor[7,8].

Fiberscope

The fiberscope used was an Olympus IF6D4-11 Industrial Ultra Thin fiberscope. The working length of the fiber is 39 in. (99 cm) with a diameter of 0.020 in. (0.51 mm) (Figure 2). The diopter adjustment ring was configured for a camera attachment. The light cable guide sprouted from the side of the control/eyepiece section. It contains a bundle of light guide fibers and its free end, called the connector, attached to an Olympus ILK-4 Cold Light Supply (100 W). The insertion tube contains the fiber bundle with a teflon coating, which was inserted into the capillary tube. The light guide within the insertion tube transmitted light from the light source to illuminate an object viewed through the objective lens at the end of the fiber bundle. The objective lens has a 60-degree field of view, with a 0.04 to 2.0 in. (1 mm to 5 cm) depth of field[9].

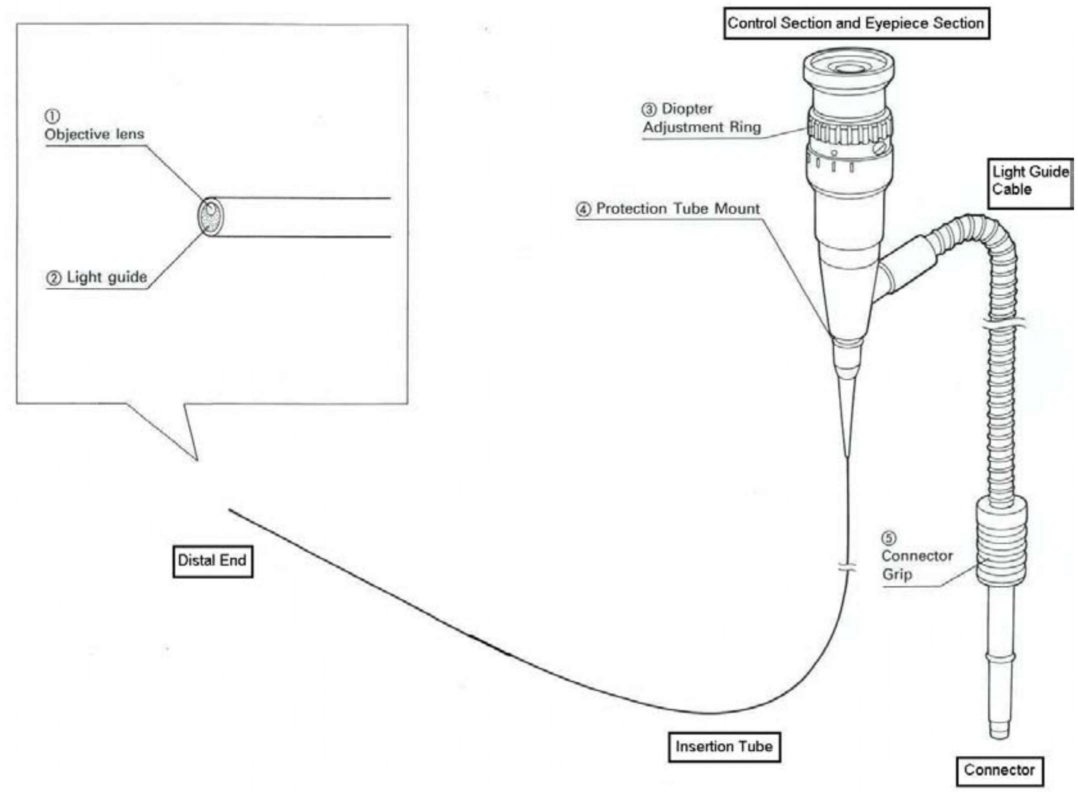

Figure 2. Fiberscope unit[9].

A Sony DCR-TRV20 camcorder recorded the flow field images seen through the fiberscope. A video display unit was connected in series with the camera to allow for a larger view during experiments. Playback features of the camcorder were utilized in evaluating the data. By playing the recorded trial frame by frame (each frame captures 1/30th of a second), the two-phase flow field was analyzed.

The fiberscope is very delicate and required special considerations. A fitting was designed that allowed the scope's fiber bundle to be inserted into the pressurized refrigeration system, but gently sealed and supported the fiber bundle so that it would not be crushed (Figure 3). The fitting was a modified compression fitting for which the standard ferrule was replaced by a sleeve made from an o-ring. An outer compression nut allowed for a gradual increase in the uniform radial pressure on the fiber bundle. The fitting held tight against the inlet pressures tested, which are considered within a normal application range for a capillary tube application with R-134a.

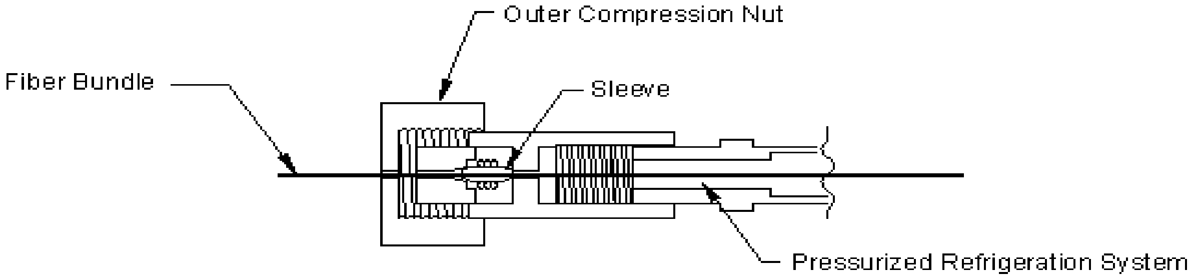

Figure 3. Fiberscope fitting.

A platform was designed and built to support the fiberscope assembly. The platform body was composed of Unistrut steel channel along with a sized piece of plywood on top providing the platform, which was all attached to the upstream-end of the existing capillary tube test stand. A thick layer of foam padding was placed on the platform, on which the actual fiberscope rested. The fiberscope was secured in place using plastic ties.

Experimental Procedures

All test point runs on the capillary tube test stand are executed using a standard operating procedure. Before allowing refrigerant to flow through the capillary tube, the exit conditions were established in the receiver and the inlet pressure set in the accumulator. The starting point for the test point reported was a steady-state room temperature inlet condition at 115.8 psia (798.4 kPa), which corresponded roughly to a 20°F (11°C) nominal inlet subcooled level. Once inlet and exit pressures are set, an upstream valve was opened allowing refrigerant to flow through the capillary tube. The refrigerant temperature at the capillary tube inlet was gradually increased while the inlet pressure was held constant by the bladder accumulator, thus reducing the inlet subcooled level.

The capillary tube was instrumented with 10 type-T thermocouples along the length, spaced at 6 in. (15.2 cm) apart starting at 12 in. (30.5 cm) downstream of the tube inlet. These wall thermocouples were firmly attached to the capillary tube outer wall using plastic wire wraps and high conductivity thermal paste. The capillary tube was a standard drawn copper tube and well insulated, therefore the indicated steady-state temperature along the wall was assumed equal to the refrigerant temperature. Immersion thermocouples were used to measure the refrigerant inlet and exit temperatures.

The fiberscope's insertion tube was inserted directly into the 0.076 in. (1.93 mm) inner diameter capillary tube from the upstream end (Figure 4). The original goal for the testing was to view the onset of vaporization from an upstream position just above the flash point location. For a constant inlet pressure the flash point location should gradually move upstream as the inlet temperature is gradually increased. However, in practice the flash point location jumps upstream in incremental steps. This jumping phenomenon made it very difficult to position the flash point at a specific location downstream *and* within the depth of field of the fiberscope lens. For the test results presented, the fiberscope lens was positioned immediately downstream of the flash point.

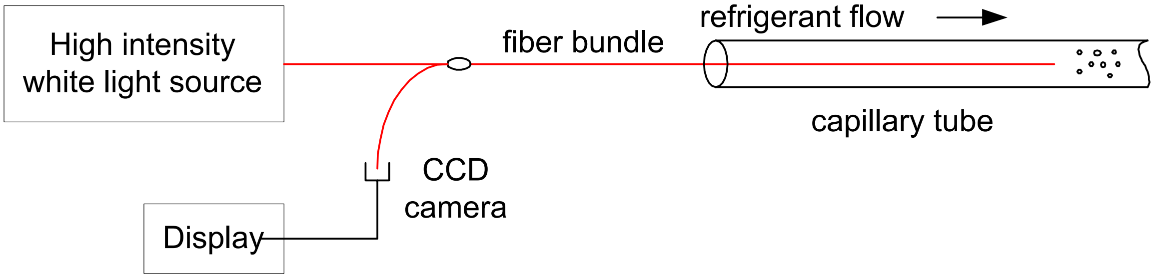

Figure 4. Visual inspection system for observation of two-phase flow inside a capillary tube. In this case, the fiberscope enters from the inlet and is viewing the onset of vaporization.

It was recognized that the presence of the probe could possibly disturb the flow field. However, using the smallest diameter fiberscope available minimized the disturbance. The 0.020 in. (0.51 mm) fiberscope is currently the smallest available bundle size that will transmit an image, and the 0.076 in. (1.93 mm) capillary tube is considered a larger-sized capillary tube. This combination results in the probe area being approximately 6% of the tube flow area (Figure 5).

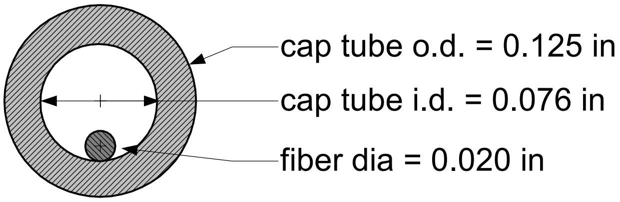

Figure 5. Scale drawing of a capillary tube's cross-section and fiber.

Experimental Results

The measured temperature profile along the capillary tube from a single steady-state test point are given in Figure 6, along with the mass flow rate, inlet pressure and inlet temperature, and exit pressure. For an adiabatic capillary tube with a subcooled liquid inlet condition, the refrigerant temperature in the capillary tube remains constant at the inlet temperature as long as the refrigerant remains a liquid. The sudden drop in the temperature along the tube profile identifies the flash point location. The flash point location of Figure 6 is located between 30 and 36 in. where the temperature drops from 80.5°F to 76.7°F. The fiberscope probe lens position is located 32 in. downstream, and the field of view looks downstream from that point. Since the fiberscope images of two-phase flow shown in Figure 8 corresponded to the temperature profile of Figure 6, then it can be further concluded that the flash point location is between 30 and 32 in.

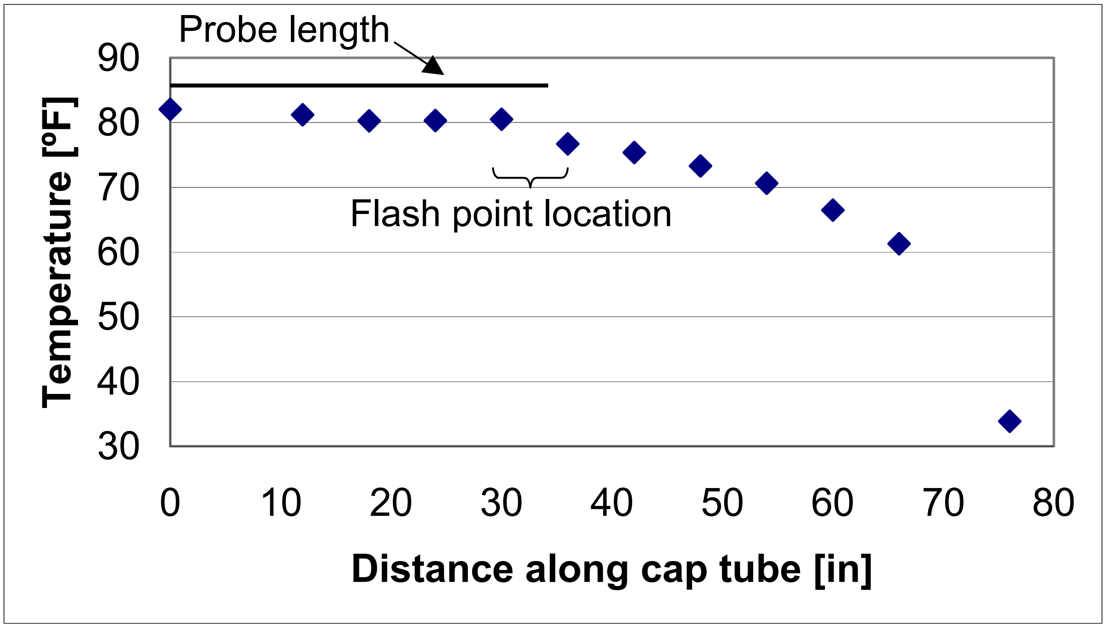

Figure 6. Measured temperature profile along capillary tube (0.076 in. diameter, 76 in. long). Mass flow rate = 1.42 lbm/min, T_{inlet}=81.5ºF, P_{inlet}=115.8 psia, and P_{exit}=46.8 psia.

What can be seen through the fiberscope is a contrast between the liquid and vapor phases. When only liquid is present, the cross-sectional view recorded by the camera depicts a dark gray region as seen in Figure 7a. When vapor is moving through the field of view, the image is much brighter as seen in Figure 7b.

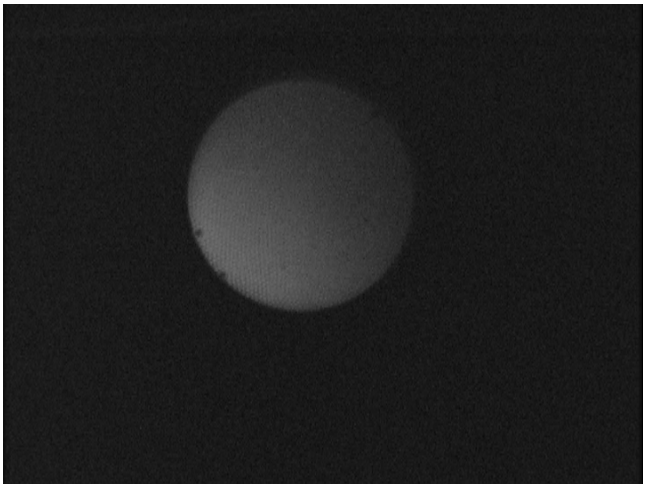

Figure 7a. Cross-sectional view of liquid R-134a in a capillary tube.

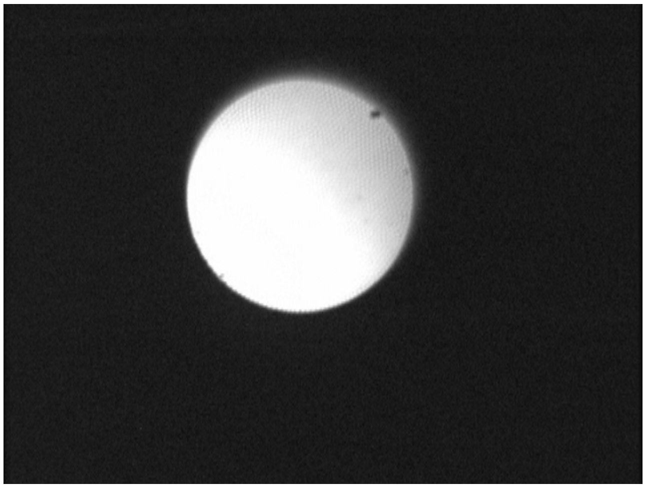

Figure 7b. Cross-sectional view of two-phase flow of R-134a in a capillary tube. The brighter area depicts the vapor phase.

The series of 12 consecutive frames shown in Figure 8 were recorded during the time the data in Figure 6 were obtained. These pictures show the two-phase flow immediately downstream of the flash point. Beginning with a complete liquid phase of frame 1 (at 25:24:01), the vapor region first appears in the lower left perimeter of frame 2, expands further in frame 3, then contracts back to the liquid state in frame 5. Frame 3 shows a well-defined curved liquid-vapor interface. What is seen in frames 1 through 5 is a vapor plug passing by. A vapor plug is a larger elongated vapor bubble within a liquid phase. This progression repeats itself between frames 5 and 12, and in this case the vapor plug is longer in length. The fields of view shown in Figure 8 are never completely 100% vapor, indicating the lower quality condition expected immediately downstream of the flash point. Occasionally, a larger vapor region passes by in quick succession of frames as shown in Figure 9. Due to the nature of the fiberscope, the length of the vapor plugs could not be determined based on the data. When the vapor plug passes by the fiberscope lens, the vapor region can be seen immediately. As the vapor plug moves beyond the lens and liquid backfills around the lens, the fiberscope will continue to view the contrast between the vapor and liquid phases as the vapor moves through and beyond the depth of field.

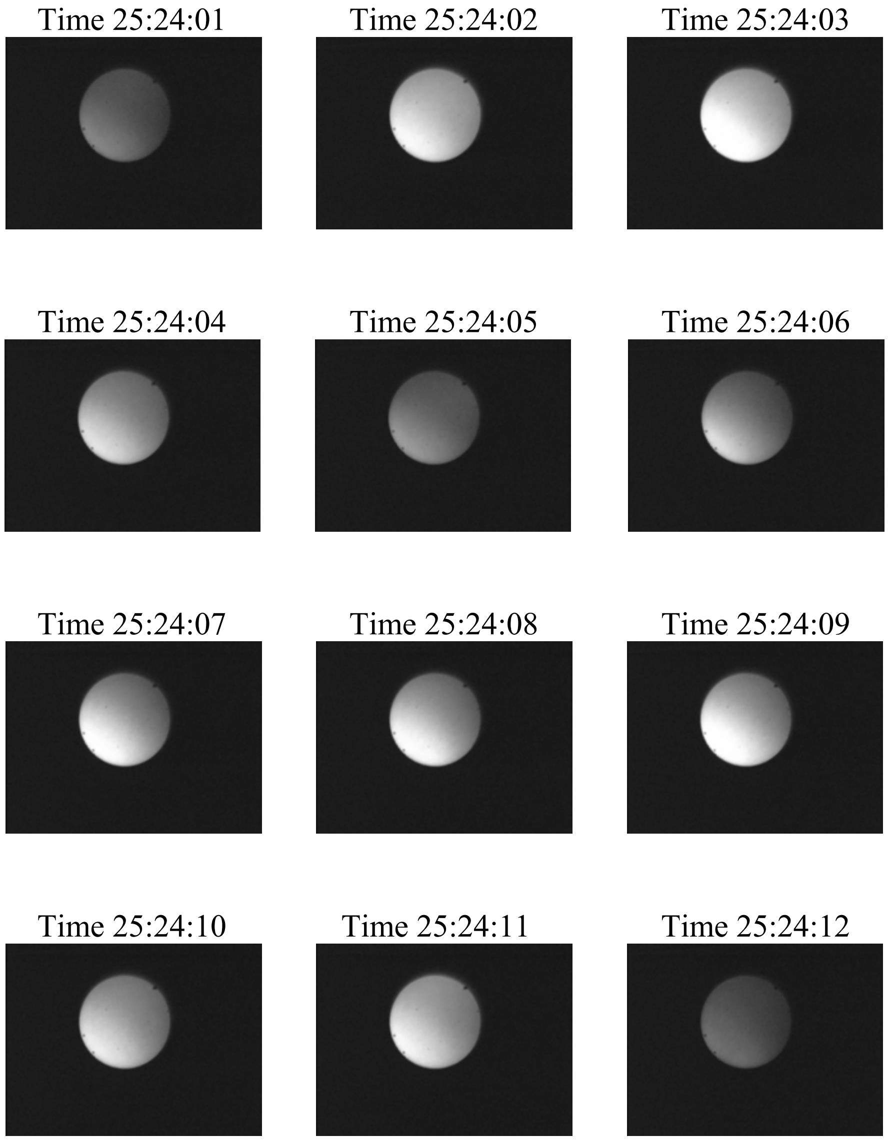
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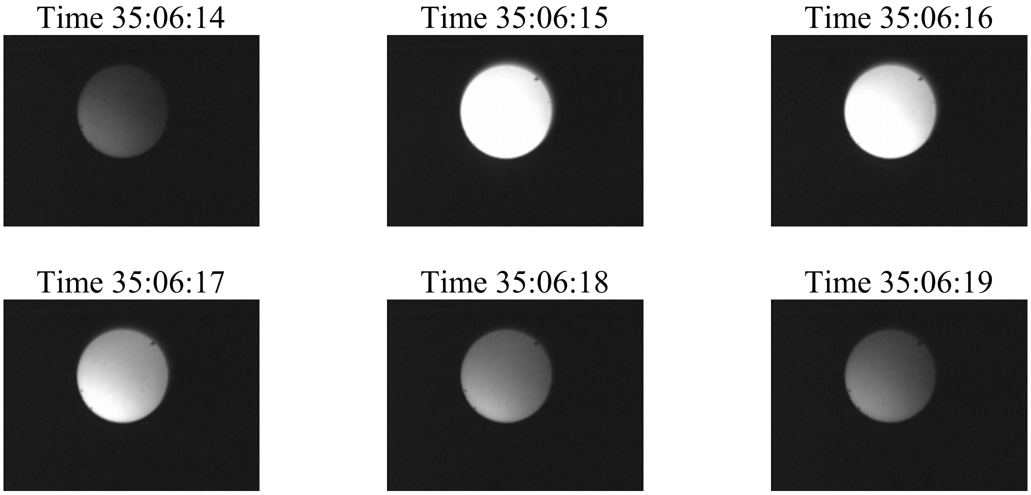
Figure 8. Sequential series of two-phase R-134a flow depicting the growth and decay of two-phase flow.


Time 35:06:14
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Time 35:06:19

Figure 9. Sequential series of two-phase R-134a flow depicting the quick growth of a large vapor region during two-phase flow.

In terms of accepted horizontal two-phase flow patterns terminology, the nature of the two-phase flow just downstream of the flash point appears to be plug/slug-type. No evidence was seen of small bubbles traversing down the centerline of the capillary tube, or of a steady fog-like appearance. This contrasts previous work by Mikol and Dudley and Mikol, which described a stream of tiny bubbles migrating to the center of the capillary tube after initiating at or near the capillary tube wall[2,10]. It also contrasts studies by Yana Motta et al. and Cooper et al. that ascertained that the two-phase flow looked to be fog-like[4,1]. Cooper et al. went on to say that no slug or bubble flow was evident[1]. These differences in the two-phase flow patterns seen in the previous studies with glass capillary tubes and those reported herein are likely due to the differences in the wall roughness, which influence the two-phase flow development.

Conclusions and Recommendations

A new method for viewing two-phase flow in a capillary tube using a fiberscope has been presented. The method is unique in that the fiberscope is inserted inside the capillary tube and the two-phase flow viewed from the inside. All previous capillary tube flow visualization studies have used glass capillary tubes, through which the flow field is viewed and photographed. By using the fiberscope inserted into the capillary tube, the fiberscope images depict a cross-sectional view of the contrast between the vapor and liquid regions during two-phase flow. A key advantage of using the fiberscope is that the two-phase flow can be observed in real applications.

In this study it was concluded that the two-phase flow pattern immediately downstream of the flash point is plug/slug-like flow, not bubbly or fog-like as reported in earlier studies using a glass capillary tube. The likely reason is because a drawn copper capillary tube has a rougher wall surface in comparison to the wall surface of a glass capillary tube. The impact of this work will be in capillary tube flow modeling and predictions of pressure drop and mass flow rate.

The near-term future plans for the effort include to continual refinement of the testing procedures in order to view the actual flash point from an upstream vantage point.

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