Chapter 1

Video Gallery of Flow Phenomena

Summary: Numerous videos have been assembled here for two-phase flows and heat transfer phenomena (and still more will be added in the future) and are available here for the reader to view. Presently, only two-phase videos are shown but videos of single-phase enhancement phenomena will be included in the future.

1.1 INTRODUCTION TO THE VIDEO GALLERY

The motive behind the preparation of this video gallery is to make videos of single-phase and two-phase flow and heat transfer phenomena available for general viewing. For thermal designers normally performing computer calculations on heat exchangers, this is an opportunity for them to actually see what some of the processes really look like, albeit in idealized test conditions. The idea is also to make this chapter a forum to display interesting videos of such phenomena for others to see.

Note: Since the original video files are typically too large (5-40 Megabits) to view directly via the internet, the videos shown have had to cut to short time sequences (typically 2 seconds or less) that are looped to give the sensation of a continuous process and also processing of the images has been applied to achieve smaller file sizes, but at a small lose of quality. Some patience may be required on behalf of the reader to view these video files via the Internet.

To use this chapter: The chapter is organized by type of flow. Within each section, videos are listed by the flow process they show; the reader needs only to click on the video of his choice on the list to see the video and also obtain a brief description of the test setup and experimental conditions.

1.2 TWO-PHASE FLOW PATTERNS IN HORIZONTAL TUBES

Figure 1.1 depicts a two-phase flow pattern map for flow in a horizontal tube, illustrating the types of two-phase flow patterns typical of these flows and the range of conditions where particular flow regimes occur. Within a horizontal evaporator tube, Figure 1.2 depicts a composite diagram of the flow patterns that may be encountered when going from a subcooled liquid to complete evaporation. Similarly, Figure 1.3 shows composite diagrams of flow patterns confronted in condensation at high and low flow rates. The videos in this section, listed below, show numerous examples of these flows.

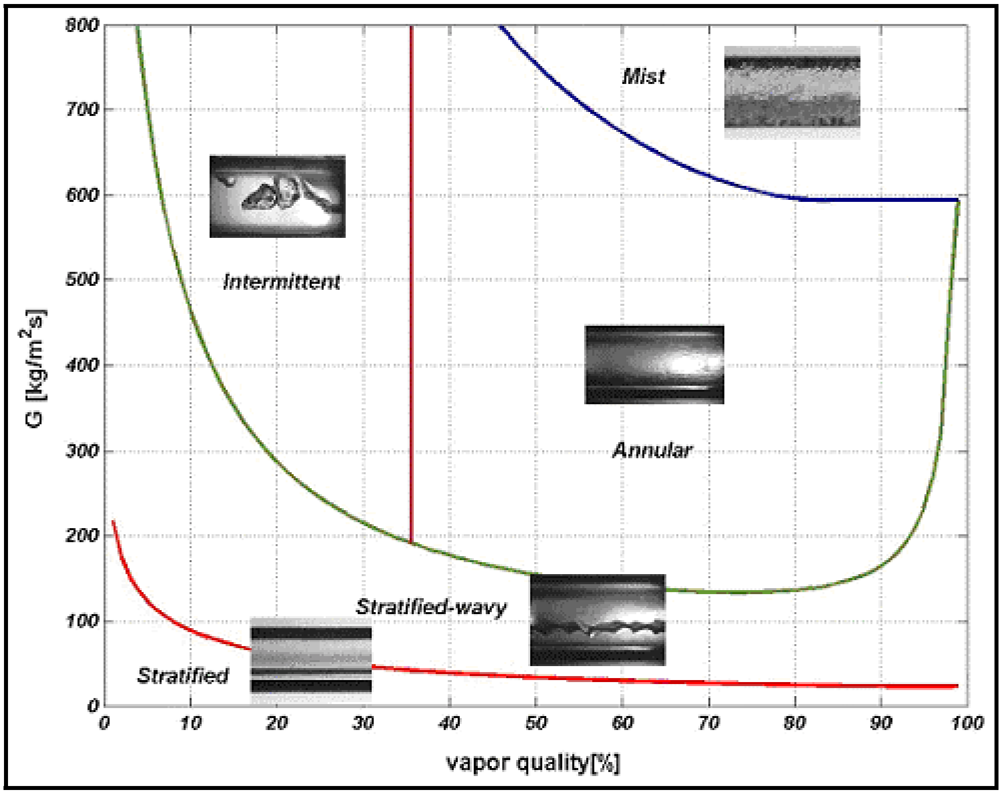

Figure 1.1. Flow pattern map for R-22 at a saturation temperature of 5°C (41°F) showing transition boundaries between two-phase flow regimes [where G is the mass velocity of the liquid + vapor inside the cross-section of the tube of internal diameter d = 13.82 mm (0.544 in.)].

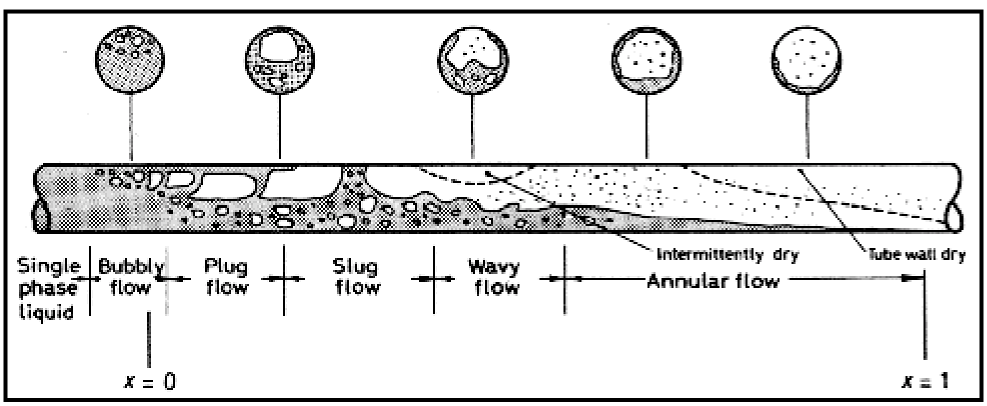

Figure 1.2. Illustration of two-phase flow patterns occurring in horizontal evaporator tube.

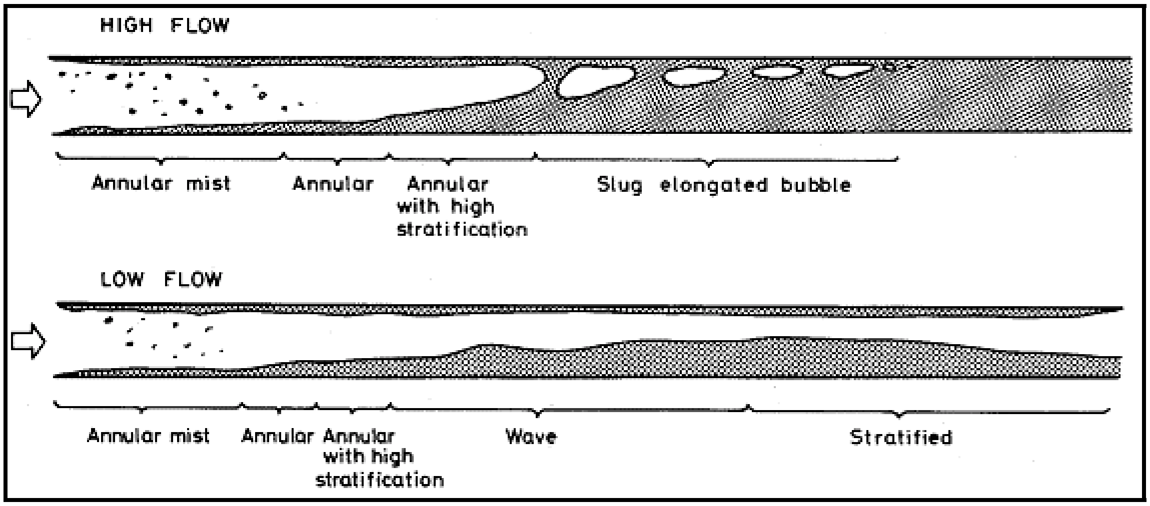

Figure 1.3. Illustration of two-phase flow patterns occurring in horizontal condenser tubes.

List of videos: (click on the one you wish to see)

Video 1.2.1: ***Bubble flow***. The video displays flow of isolated bubbles inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. This flow is at a moderate mass velocity at a very low vapor quality and the bubble is essentially the initial step towards arriving at a plug flow. The fluid is ammonia at 5°C (41°F). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, O. Favrat, D. and Thome, J.R. (2001), Development of a Diabatic Two-Phase Flow Pattern Map for Horizontal Flow Boiling, *Int. J. Heat Mass Transfer*, Vol. 45, pp. 291-301.

Video 1.2.2: ***Stratified-wavy flow***. The video displays a stratified-wavy flow (liquid in bottom and vapor in top of tube) inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5°C (41°F), a vapor quality of 0.20 and mass velocity of 26 kg/m^2s (19126 lb/hr ft^2). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, O. Favrat, D. and Thome, J.R. (2001), Development of a Diabatic Two-Phase Flow Pattern Map for Horizontal Flow Boiling, *Int. J. Heat Mass Transfer*, Vol. 45, pp. 291-301.

Video 1.2.3: ***Plug/slug to intermittent flow transition***. The video displays a plug/slug flow at relatively low vapor quality inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5°C (41°F), a vapor quality of 0.06 and mass velocity of 180 kg/m^2s (132408 lb/hr ft^2). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, O. Favrat, D. and Thome, J.R. (2001), Development of a Diabatic Two-Phase Flow Pattern Map for Horizontal Flow Boiling, *Int. J. Heat Mass Transfer*, Vol. 45, pp. 291-301.

Video 1.2.4: ***Annular flow***. The video displays an annular flow (liquid in an annular film on tube perimeter and vapor in center of tube) at relatively high vapor quality inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5°C (41°F), a vapor quality of 0.80 and mass velocity of 122 kg/m^2s (89743 lb/hr ft^2). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, O. Favrat, D. and Thome, J.R. (2001), Development of a Diabatic Two-Phase Flow Pattern Map for Horizontal Flow Boiling, *Int. J. Heat Mass Transfer*, Vol. 45, pp. 291-301.

Video 1.2.5: ***Annular flow with partial dryout***. The video displays an annular flow with partial dryout around the upper perimeter (liquid in bottom and vapor in top of tube) at relatively high vapor quality (*essentially a stratified-wavy flow created by the partial dryout around upper perimeter of the tube*) inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5°C (41°F), a vapor quality of 0.80 and mass velocity of 41 kg/m^{2}s (30160 lb/hr ft^2). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, O. Favrat, D. and Thome, J.R. (2001), Development of a Diabatic Two-Phase Flow Pattern Map for Horizontal Flow Boiling, *Int. J. Heat Mass Transfer*, Vol. 45, pp. 291-301.

Video 1.2.6: ***Condensation flow regimes in plain tube***. The video displays the exit of a horizontal condenser tube cut at a 45° degree angle and situated inside a viewing chamber. The view is from the side. First, a flow pattern map is shown illustrating two superficial vapor velocities, J_G, that were studided, plotted versus the Martinelli parameter, X_{tt}. The inside diameter of the tube is 8.0 mm (0.315 in.). The fluid is R-134a at 40°C (104°F), vapor qualities (x) of 0.49 and 0.26, and mass velocities (G) of 200 and 400 kg/m^{2}s (147120 and 294240 lb/hr ft^2). The video was taken under the direction of Prof. Alberto Cavallini at the University of Padova, Padova, Italy. For a description of their test facility and related investigation, refer to: Censi G., Doretti L., Rossetto L., Zilio C., Flow Pattern Visualisation during Condensation of R134a inside Horizontal Microfin and Smooth Tubes, 21st IIR Int. Congress of Refrigeration, Washington DC, USA August 17-22, (2003). For a description of their flow pattern map, refer to: Cavallini A., Censi G., Del Col D., Doretti L., Longo G.A., Rossetto L., Intube Condensation of Halogenated Refrigerants, Paper H-1718, *ASHRAE Trans*., Vol. 108, pt. 1 (2002).

Video 1.2.7: ***Condensation flow regimes in microfin tube***. The video displays the exit of a horizontal condenser tube cut at a 45° degree angle and situated inside a viewing chamber. The view is from the side. First, a flow pattern map is shown illustrating two superficial vapor velocities, J_G, that were tested plotted versus the Martinelli parameter, X_{tt}. The inside diameter at the fin tip is 7.69 mm (0.303 in.). The fluid is R-134a at 40°C (104°F), vapor qualities (x) of 0.51 and 0.25, and mass velocities (G) of 200 and 400 kg/m^{2}s (147120 and 294240 lb/hr ft^2). This video can be compared to the plain tube video 1.2.6 and it is seen that the microfins imposed a more uniform distribution of liquid around the tube perimeter, especially at the lower mass velocity. The video was taken under the direction of Prof. Alberto Cavallini at the University of Padova, Padova, Italy. For a description of their test facility and related investigation, refer to: Censi G., Doretti L., Rossetto L., Zilio C., Flow Pattern Visualisation during Condensation of R134a inside Horizontal Microfin and Smooth Tubes, 21st IIR Int. Congress of Refrigeration, Washington DC, USA August 17-22, (2003). For a description of their flow pattern map, refer to: Cavallini A., Censi G., Del Col D., Doretti L., Longo G.A., Rossetto L., Intube Condensation of Halogenated Refrigerants, Paper H-1718, *ASHRAE Trans*., Vol. 108, pt. 1 (2002).

Video 1.2.8: ***Annular flow with entrainment of liquid droplets***. The video displays a side view of annular flow with a large number of small liquid droplets in a high velocity vapor core of the flow, inside a horizontal sightglass of 13.6 mm (0.535 in.) internal diameter. The fluid is R-22 at 5°C (41°F), a vapor quality of 0.65 and mass velocity of 600 kg/m^{2}s (441000 lb/hr ft^2). The video was taken by L. Wojtan in collaboration with Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Ursenbacher, T., Wojtan, L., Thome, J.R. (2004). Dynamic Void Fractions in Stratified Types of Flow, Part I: New Optical Measurement Technique. *Int. J. Multiphase Flow*, Vol. 31, in press *and* Wojtan, L., Ursenbacher, T., Thome, J.R. (2004). Dynamic Void Fractions in Stratified Types of Flow, Part II: Measurements for R-22 and R-410a. *Int. J. Multiphase Flow*, Vol. 31, in press.

Video 1.2.9: ***Transition from annular to mist flow***. The video displays a side view of a flow in the transition regime between annular flow with liquid entrainment (lower portion of tube) and mist flow (upper portion of tube), inside a horizontal sightglass of 13.6 mm (0.535 in.) internal diameter. The fluid is R-22 at 5°C (41°F), a vapor quality of 0.79 and mass velocity of 500 kg/m^{2}s (367500 lb/hr ft^2). The video was taken by L. Wojtan in collaboration with Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Ursenbacher, T., Wojtan, L., Thome, J.R. (2004). Dynamic Void Fractions in Stratified Types of Flow, Part I: New Optical Measurement Technique. *Int. J. Multiphase Flow*, Vol. 31, in press *and* Wojtan, L., Ursenbacher, T., Thome, J.R. (2004). Dynamic Void Fractions in Stratified Types of Flow, Part II: Measurements for R-22 and R-410a. *Int. J. Multiphase Flow*, Vol. 31, in press.

Video 1.2.10: ***Mist flow***. The video displays a cross-sectional view of mist flow (small liquid droplets in a high velocity vapor flow) inside a horizontal sightglass of 13.6 mm (0.535 in.) internal diameter. The fluid is R-22 at 5°C (41°F), a vapor quality of 0.90 and mass velocity of 400 kg/m^{2}s (294000 lb/hr ft^2). The cross-section of the tube is illuminated by a laser sheet and the liquid is highlighted by a trace of fluorescent powder. The video was taken by L. Wojtan in collaboration with Prof. J.R. Thome and Dr. T. Ursenbacher at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Ursenbacher, T., Wojtan, L., Thome, J.R. (2004). Dynamic Void Fractions in Stratified Types of Flow, Part I: New Optical Measurement Technique. *Int. J. Multiphase Flow*, Vol. 31, in press *and* Wojtan, L., Ursenbacher, T., Thome, J.R. (2004). Dynamic Void Fractions in Stratified Types of Flow, Part II: Measurements for R-22 and R-410a. *Int. J. Multiphase Flow*, Vol. 31, in press.

Video 1.2.11: ***Annular flow with twisted tape insert at low mass velocity***. The video displays an annular flow with swirl from a twisted tape for flow inside a horizontal sight glass of 8.0 mm (0.315 in.) internal diameter. The fluid is R-507A at 5°C (41°F), a vapor quality of 0.33 and mass velocity of 100 kg/m^{2}s (73500 lb/hr ft^2). In a plain tube without twisted tape, the flow would be stratified-wavy and it is clear that the tape converts the flow to annular flow, including some liquid entrainment. The video was taken by J. Moreno Quiben in collaboration with Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility (*without the twisted tape*), refer to: J. Moreno Quiben and J.R. Thome, Two-Phase Pressure Drops in Horizontal Tubes: New Results for R-410A and R-134a Compared to R-22, 21st IIR International Congress of Refrigeration, Washington, D.C., Aug. 17-22, Paper ICR045 (2003).

Video 1.2.12: ***Annular flow with twisted tape insert at medium mass velocity***. The video displays an annular flow with swirl from a twisted tape for flow inside a horizontal sight glass of 8.0 mm (0.315 in.) internal diameter. The fluid is R-507A at 5°C (41°F), a vapor quality of 0.18 and mass velocity of 150 kg/m^{2}s (147100 lb/hr ft^2). The flow is annular with a swirl effect from the tape and some liquid entrainment. The video was taken by J. Moreno Quiben in collaboration with Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility (*without the twisted tape*), refer to: J. Moreno Quiben and J.R. Thome, Two-Phase Pressure Drops in Horizontal Tubes: New Results for R-410A and R-134a Compared to R-22, 21st IIR International Congress of Refrigeration, Washington, D.C., Aug. 17-22, Paper ICR045 (2003).

Video 1.2.13: ***Annular flow with twisted tape insert at high mass velocity***. The video displays an annular flow with swirl from a twisted tape for flow inside a horizontal sight glass of 8.0 mm (0.315 in.) internal diameter. The fluid is R-507A at 5°C (41°F), a vapor quality of 0.20 and mass velocity of 300 kg/m^{2}s (220500 lb/hr ft^2). The flow is annular with a swirl effect from the tape and some liquid entrainment. The video was taken by J. Moreno Quiben in collaboration with Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility (*without the twisted tape*), refer to: J. Moreno Quiben and J.R. Thome, Two-Phase Pressure Drops in Horizontal Tubes: New Results for R-410A and R-134a Compared to R-22, 21st IIR International Congress of Refrigeration, Washington, D.C., Aug. 17-22, Paper ICR045 (2003).

1.3 VOID FRACTION MEASUREMENTS IN HORIZONTAL TUBES

Dynamic cross-sectional void fractions have been measured at the Laboratory of Heat and Mass Transfer (LTCM) at the Swiss Federal Institute of Technology Lausanne (EPFL). In Figure 1.4, the simplified diagram of the experimental visualization setup is shown where the two-phase refrigerant flows inside the horizontal tube and is viewed from an oblique angle through the glass tube wall by the camera. The effects refraction through the glass tube wall and oblique view of the flow cross-section by the camera objective are taken into account in reconstruction of the true image, such that the flow structure can be analysed as described in Figure 1.5. For a complete description, refer to: Ursenbacher, Wojtan and Thome (2004) and Wojtan, Ursenbacher and Thome (2004).

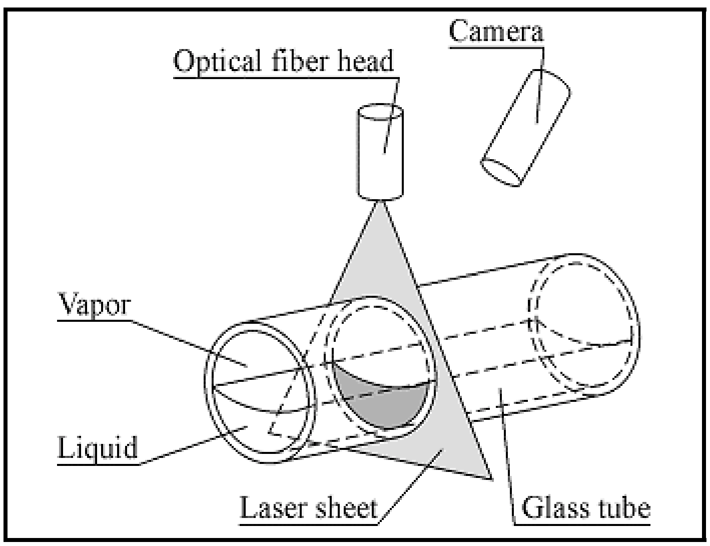

Figure 1.4. Cross-sectional void fraction visualization setup for a stratified flow in a horizontal tube.

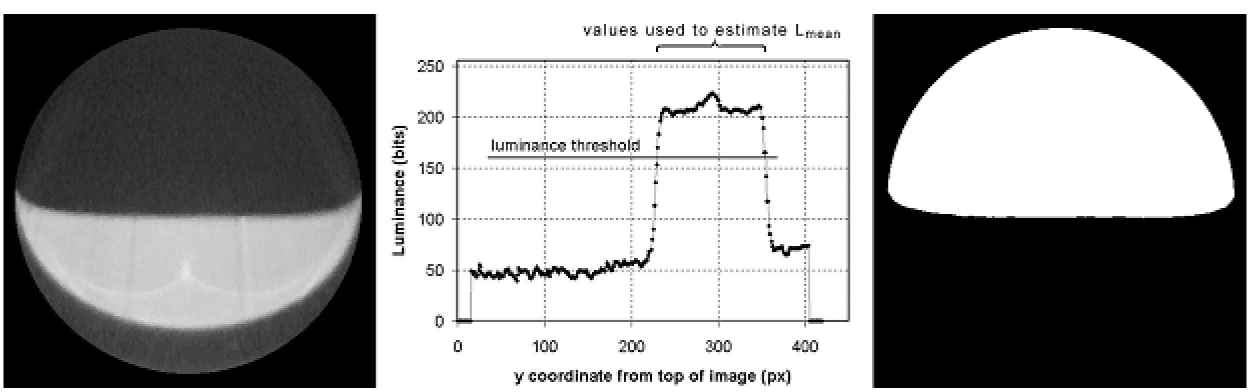

Figure 1.5. Left: Transformed cross-sectional image from actual video image of flow; Middle: variation in luminance intensity along the center vertical line of image; Right: Detected vapor (white) and liquid (black) zones in the tube, depicting shape of interface, dry angle around upper perimeter of tube and dynamic void fraction, i.e. number of white pixels divided by number of all white and black pixels.

List of videos: (click on the one you wish to see)

Video 1.3.1: ***Overall view of air-water test facility with a slug flow***. The video shows the LTCM air-water test facility for observing two-phase flows and measuring void fractions inside a horizontal sight glass of 13.8 mm (0.543 in.) internal diameter. The liquid is water and the gas is air at room temperature. The video was taken in Laboratory of Heat and Mass Transfer under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.3.2: ***Close up of air-water loop showing the video camera with a slug flow***. The video shows LTCM test facility for observing two-phase flows and measuring void fractions inside a horizontal sight glass of 13.8 mm (0.543 in.) internal diameter. The video shows the placement of the video camera above the glass tube for taking void fraction videos. The liquid is water and the gas is air at room temperature. The video was taken in Laboratory of Heat and Mass Transfer under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.3.3: ***Air-water test loop with laser sheet cutting across tube just below camera***. The video shows a vertical laser sheet cutting across a horizontal tube for a slug flow inside a horizontal sightglass of 13.8 mm (0.543 in.) internal diameter. The video camera for recording the cross-section of the flow at the laser sheet is located just above and to the right of the images to be recorded. The second tube is only there for some other preliminary tests. The liquid is water and the gas is air at room temperature. The video was taken in Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.3.4: ***Original video of slug flow with effects of refractions of light***. The video shows the original view image (in slow motion) of the cross-section of the two-phase flow inside a horizontal sightglass of 13.8 mm (0.543 in.) internal diameter with the cross-sectional image compressed and distorted by the angle of the camera and the refraction of light through the glass tube wall. The liquid is water and the gas is air at room temperature. The video was taken in Laboratory of Heat and Mass Transfer by L. Wojtan under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The video is not at actual speed.

Video 1.3.5: ***Transformed video of same slug flow video***. The video shows the corrected video image (slow motion) of Video 1.3.4 in black and white inside a horizontal sightglass of 13.8 mm (0.543 in.) internal diameter, showing the cross-sectional view of the flow. The liquid is water (white) and the gas (black) is air at room temperature. The black areas *below* the liquid interface are caused by reflections and do not represent gas. The video was processed in Laboratory of Heat and Mass Transfer (LTCM) by Dr. T. Ursenbacher under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The video is not at actual speed.

Video 1.3.6: ***Black-and-white version of transformed image of same slug flow video***. The video shows the digitized image (slow motion) of a slug flow inside a horizontal sightglass of 13.8 mm internal diameter. The liquid occupies the lower portion of the tube (black) and the vapor the upper portion of the tube (white). The number of white pixels divided by the total pixels of the tube cross-section gives the instantaneous void fraction for each video image. The dry angle around the upper perimeter of the tube changes during the flow. The liquid is water and the gas is air at room temperature. The video was processed in the Laboratory of Heat and Mass Transfer (LTCM) by Dr. T. Ursenbacher under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The video is not at actual speed.

Video 1.3.7: ***R-410A slug flow video showing measured interfacial contour***. The video shows the digitized image of a slug flow inside a horizontal sightglass of 13.6 mm (0.535 in.) internal diameter. The liquid occupies the lower portion of the tube (white) and the vapor the upper portion of the tube (grey). The interface contour detected by the image processing program is superimposed on each image. The number of pixels above the interfacial contour divided by the total pixels of the tube cross-section gives the instantaneous void fraction for each video image. The dry angle around the upper perimeter of the tube is evident and changes during the flow. When liquid slugs pass by, the total cross-section is occupied by liquid. The fluid is R-410A at 5°C (41°F), a vapour quality of 0.103 and a mass velocity of 150 kg/m^{2}s (110340 lb/hr ft^2). The video was obtained and processed in the Laboratory of Heat and Mass Transfer (LTCM) by L. Wojtan and Dr. T. Ursenbacher under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The video is at actual speed. The work is described in: Wojtan, L., Ursenbacher, T. and Thome, J.R. (2003). Interfacial Measurements in Stratified Types of Flow. Part II: Measurements of R-22 and R-410A, *Int. J. Multiphase Flow* (in review).

Video 1.3.8: ***R-410A stratified-wavy flow video showing measured interfacial contour***. The video shows the digitized image of a stratified-wavy flow inside a horizontal sightglass of 13.6 mm (0.535 in.) internal diameter. The liquid occupies the lower portion of the tube (white) and the vapor the upper portion of the tube (grey). The interface contour detected by the image processing program is superimposed on each image. The number of pixels above the interfacial contour divided by the total pixels of the tube cross-section gives the instantaneous void fraction for each video image. The dry angle around the upper perimeter of the tube is evident and changes during the flow. The movement of the contour with time is the result of the interfacial waves created by the vapour shear of the vapor on the liquid. The fluid is R-410A at 5°C (41°F), a vapour quality of 0.20 and a mass velocity of 70 kg/m^{2}s (51492 lb/hr ft^2). The video was obtained and processed in the Laboratory of Heat and Mass Transfer (LTCM) by L. Wojtan and Dr. T. Ursenbacher under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The video is at actual speed. The work is described in: Wojtan, L., Ursenbacher, T. and Thome, J.R. (2003). Interfacial Measurements in Stratified Types of Flow. Part II: Measurements of R-22 and R-410A, *Int. J. Multiphase Flow* (in review).

1.4 TWO-PHASE FLOW PATTERNS IN VERTICAL TUBES

Example sketches of some of the typical two-phase flow patterns (mist flow is not shown) occurring in a vertical tube are shown in Figure 1.6. The first five videos below show the transition from a bubbly flow to a slug flow via bubble clustering.

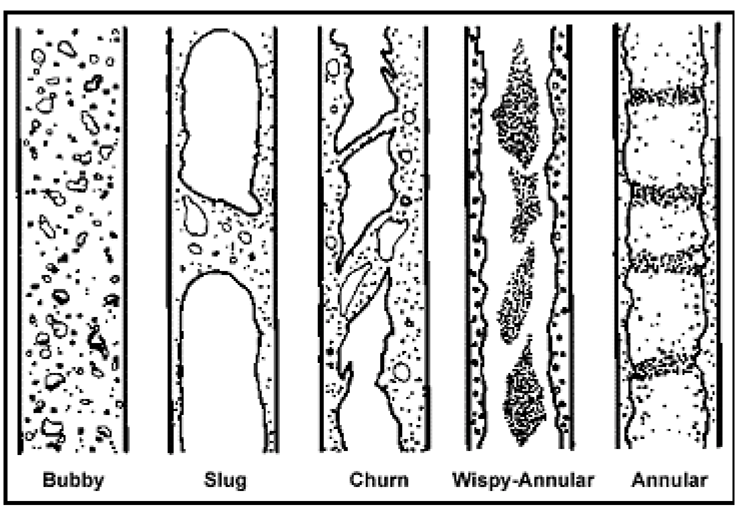

Figure 1.6. Illustration of two-phase flow patterns occurring in vertical evaporator tube.

List of videos: (click on the one you wish to see)

Video 1.4.1: ***Dispersed bubble flow of air-water at void fraction of 5.1%***. The video shows a bubbly flow inside a vertical glass tube of 30 mm (1.181 in.) internal diameter. The liquid is water and the gas is air at ambient temperature. The flow is at a gas phase superficial velocity of 0.021 m/s and a liquid superficial velocity of 0.21 m/s. The flow depicts dispersed bubbles that have not yet begun to form into clusters. The video is at actual speed. The void fraction was measured using a microresistivity probe at the centreline of the channel. The videos were provided by the Laboratory for Fluid Dynamics and Thermodynamics (LFDT), Faculty of Mechanical Engineering, University of Ljubljana, Slovenia under the direction of Prof. Iztok Zun and were presented at the following international meeting: Zun, I. and Polutnik, E. (2001). Bubble to Slug Flow Transition: Experimental and Numerical Experience in Bubble Tracking Studies, *4th International Conference on Multiphase Flow*, New Orleans, May 27-June 1. *Note: The videos 1.4.1 through 1.4.5 should be viewed in sequential order to observe the bubble to slug flow transition process.*

Video 1.4.2: ***Bubbly flow of air-water at void fraction of 10.3% at start of clustering***. The video shows a bubbly flow inside a vertical glass tube of 30 mm (1.181 in.) internal diameter. The liquid is water and the gas is air at ambient temperature. The flow is at a gas phase superficial velocity of 0.029 m/s and a liquid superficial velocity remains the same at 0.21 m/s. The flow depicts dispersed bubbles that have begun to form into clusters. The video is at actual speed. The void fraction was measured using a microresistivity probe at the centreline of the channel. The videos were provided by the Laboratory for Fluid Dynamics and Thermodynamics (LFDT), Faculty of Mechanical Engineering, University of Ljubljana, Slovenia under the direction of Prof. Iztok Zun and were presented at the following international meeting: Zun, I. and Polutnik, E. (2001). Bubble to Slug Flow Transition: Experimental and Numerical Experience in Bubble Tracking Studies, *4th International Conference on Multiphase Flow*, New Orleans, May 2-June 1.

Video 1.4.3: ***Bubbly flow of air-water at void fraction of 13.9% with bubble clusters***. The video shows a bubbly flow with evident bubble clusters inside a vertical glass tube of 30 mm (1.181 in.) internal diameter. The liquid is water and the gas is air at ambient temperature. The flow is at a gas phase superficial velocity of 0.034 m/s and a liquid superficial velocity remains the same at 0.21 m/s. The flow depicts dispersed bubbles that have migrated together to form bubble clusters. The video is at actual speed. The void fraction was measured using a microresistivity probe at the centreline of the channel. The videos were provided by the Laboratory for Fluid Dynamics and Thermodynamics (LFDT), Faculty of Mechanical Engineering, University of Ljubljana, Slovenia under the direction of Prof. Iztok Zun and were presented at the following international meeting: Zun, I. and Polutnik, E. (2001). Bubble to Slug Flow Transition: Experimental and Numerical Experience in Bubble Tracking Studies, *4th International Conference on Multiphase Flow*, New Orleans, May 27-June 1.

Video 1.4.4: ***Bubbly flow of air-water at void fraction of 15.4% with first slugs***. The video shows a bubbly flow with the first formation of slugs inside a vertical glass tube of 30 mm (1.181 in.) internal diameter. The liquid is water and the gas is air at ambient temperature. The flow is at a gas phase superficial velocity of 0.045 m/s and a liquid superficial velocity remains the same at 0.21 m/s. The flow depicts the point of transition of bubble clusters into vapor slugs with a high density of bubbles in the wake. The video is at actual speed. The void fraction was measured using a microresistivity probe at the centreline of the channel. The videos were provided by the Laboratory for Fluid Dynamics and Thermodynamics (LFDT), Faculty of Mechanical Engineering, University of Ljubljana, Slovenia under the direction of Prof. Iztok Zun and were presented at the following international meeting: Zun, I. and Polutnik, E. (2001). Bubble to Slug Flow Transition: Experimental and Numerical Experience in Bubble Tracking Studies, *4th International Conference on Multiphase Flow*, New Orleans, May 27-June 1.

[Video 1.4.5](#): ***Slug flow of air-water at void fraction of 17.0% with remaining bubbles***. The video shows a slug flow with numerous dispersed bubbles in the liquid phase inside a vertical glass tube of 30 mm (1.181 in.) internal diameter. The liquid is water and the gas is air at ambient temperature. The flow is at a gas phase superficial velocity of 0.058 m/s and a liquid superficial velocity remains the same at 0.21 m/s. The flow depicts well established vapor slugs at these conditions. The video is at actual speed. The void fraction was measured using a microresistivity probe at the centreline of the channel. The videos were provided by the Laboratory for Fluid Dynamics and Thermodynamics (LFDT), Faculty of Mechanical Engineering, University of Ljubljana, Slovenia under the direction of Prof. Iztok Zun and were presented at the following international meeting: Zun, I. and Polutnik, E. (2001). Bubble to Slug Flow Transition: Experimental and Numerical Experience in Bubble Tracking Studies, *4th International Conference on Multiphase Flow*, New Orleans, May 27 - June 1.

1.5 ADIABATIC FALLING FILMS ON HORIZONTAL TUBE ARRAYS

Liquid films falling on horizontal tubes aligned as a vertical array (horizontal tubes one above the other) fall from tube to tube in distinct flow modes under the influence of gravity. As shown in Figure 1.7, the three principal intertube falling film flow modes are droplet, column and sheet, joined together by two transition regimes in which both droplets and columns coexist or columns and short sheets coexist. The videos illustrate these flows.

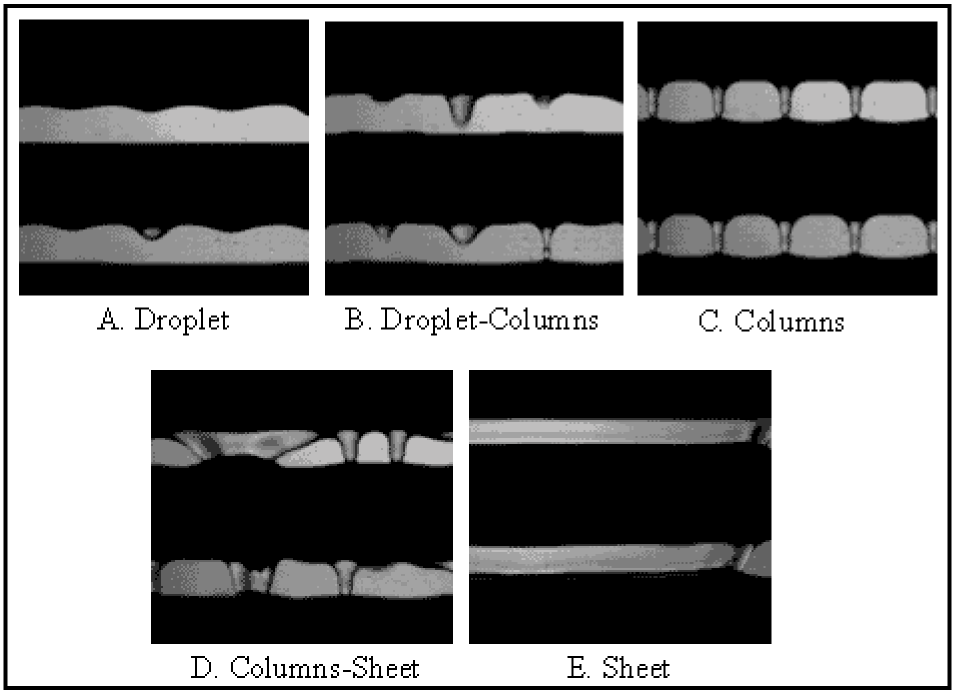

Figure 1.7. Diagram illustrating three principal intertube falling film flow modes on an array of horizontal tubes one below another (A, C and E) and the two transition regimes (B and D).

List of videos: (click on the one you wish to see)

[Video 1.5.1](#): ***Droplet flow mode***. The video shows the droplet flow mode from the bottom of the upper tube to the top of the lower tube. The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is ethylene glycol falling in ambient air. The flow is near the transition to column flow mode as evidenced by the elongation of some of the liquid droplets into columns nearly reaching the lower tube. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.2: ***Transition from droplet to column flow mode***. The video shows the transition in the flow regime from droplet flow mode to the column flow mode. The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is ethylene glycol falling in ambient air. Both droplets and columns coexist along the tube, indicating the transition regime. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.3: ***Inline column flow mode***. The video shows the inline column flow regime from the bottom of the upper tube onto the top of the lower tube. The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is ethylene glycol falling in ambient air. The columns are very stable (difficult to see any movement) and nearly equally spaced. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.4: ***Staggered column flow mode***. The video shows the staggered column flow regime from the bottom of the upper tube onto the top of the lower tube. The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is ethylene glycol falling in ambient air. The columns are quite stable and nearly equally spaced and equally staggered. The staggered regime is achieved by increasing the film flow rate, which creates a crest of liquid at the top of the tube between impinging liquid jets. The thick liquid layer at a crest then flows around the tube to form the staggered column on the bottom. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.5: ***Transition from column to sheet flow mode***. The video shows the transition from the staggered column flow regime to the sheet flow regime at intervals along the tube. The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is ethylene glycol falling in ambient air. The short width of the sheets renders them unstable and surface tension pulls them into a wedge shape. Columns and small sheets tend to coalesce. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.6: ***Sheet flow mode***. The video shows the sheet flow regime from the bottom of the upper tube to the top of the lower tube, i.e. the classic flow regime assumed for falling film condensation on tube rows by Nusselt (1916). The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is ethylene glycol falling in ambient air. The surface tension forces on the ends of the sheet tends to pull them in. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.7: ***Slow motion of transition from droplet to column mode***. The video shows a slow motion of a video out the transition of droplets to columns. The tubes are plain with diameters of 19.05 mm (0.75 in.). The liquid is water falling in ambient air. The original digital video was taken at 1000 images per second and has been slowed down for viewing. The video was obtained by J.F. Roques and V. Dupont in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). The experimental test setup and work is described in: Roques, J.F., Dupont, V. and Thome, J.R. (2002). Falling Film Transitions on Plain and Enhanced Tubes, *J. Heat Transfer*, Vol. 124, pp. 491-499.

Video 1.5.8: ***Falling film of R-134a on plain tube at low flow rate***. The video shows flow of liquid R-134a film on plain tubes of 19.05 mm (0.75 in.) with intertube spacing of 9.5 mm (0.374 in.). The R-134a is at a saturation temperature of 20°C (68°F) with a flow rate per unit length of tube equal to 0.07 kg/m s (0.047 lb/ft s). The flow mode is near the transition from droplet to column mode (predominately droplet flow is observed) but the droplet flow is rather unstable. The video was obtained by D. Gstöhl and J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.5.9: ***Falling film of R-134a on plain tube at medium flow rate***. The video shows flow of liquid R-134a film on plain tubes of 19.05 mm (0.75 in.) with intertube spacing of 9.5 mm (0.374 in.). The R-134a is at a saturation temperature of 20°C (68°F) with a flow rate per unit length of tube equal to 0.11 kg/m s (0.074 lb/ft s). The flow mode is column but they are rather unstable and cause some liquid to sling laterally off the bottom of the tube, typically observed in numerous other occasions. The video was obtained by D. Gstöhl and J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.5.10: ***Falling film of R-134a on plain tube at high flow rate***. The video shows flow of liquid R-134a film on plain tubes of 19.05 mm (0.75 in.) with intertube spacing of 9.5 mm (0.374 in.). The R-134a is at a saturation temperature of 20°C (68°F) with a flow rate per unit length of tube equal to 0.36 kg/m s (0.241 lb/ft s). The flow mode is near the transition from column to sheet but the liquid columns are unstable and cause some liquid to sling laterally off the bottom of the tube, typically observed in numerous other occasions. The video was obtained by D. Gstöhl and J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

1.6 FALLING FILM CONDENSATION ON HORIZONTAL TUBES

Condensation on horizontal tube bundles is a common process with the condensate from above tubes inundating the lower tubes. Hence, the condensate flowing from an upper tube to a lower tube characterizes the two-phase flow regime, called the intertube flow mode here.

List of videos: (click on the one you wish to see)

Video 1.6.1: ***R-134a condensing on tube array in droplet mode flow***. The video shows R-134a condensing at 30°C (86°F) on the second tube of an array of tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the second tube is 6400 W/m^2 (2030 Btu/h ft^2). The flow is in the droplet mode. Elongation of the droplets during their departure is clearly visible and the spreading of the condensate upon impact on the lower tube. The video was taken by D. Gstöhl in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.6.2: ***R-134a condensing on tube array in droplet mode near transition to column flow***. The video shows R-134a condensing at 30°C (86°F) on the sixth tube of an array of tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the sixth tube is 8100 W/m^2 (2670 Btu/h ft^2). The flow is in the droplet mode near the transition to column flow. The elongating droplets are unstable and perhaps this prevents the formation of stable columns at this condition. The video was taken by D. Gstöhl in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.6.3: ***R-134a condensing on tube array in column mode***. The video shows R-134a condensing at 30°C (86°F) on the sixth tube of an array of tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the sixth tube is 20000 W/m^2 (6340 Btu/h ft^2). The flow is in the column mode and the columns are unstable. The video was taken by D. Gstöhl in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.6.4: ***R-134a condensing on 6-tube array at low heat flux in droplet mode***. The video shows R-134a condensing at 30°C (86°F) on a six-tube array. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the top tube is 9500 W/m^2 (3010 Btu/h ft^2) and on the bottom tube is 6700 W/m^2 (2120 Btu/h ft^2). The flow is in the droplet mode from all tubes. The video was taken by D. Gstöhl in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.6.5: ***R-134a condensing on 6-tube array at medium heat flux going from droplet to column mode***. The video shows R-134a condensing at 30°C (86°F) on a six-tube array. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the top tube is 26000 W/m^2 (8240 Btu/h ft^2) and on the bottom tube is 20000 W/m^2 (6340 Btu/h ft^2). The flow is in the droplet mode at the top and progresses to column mode at the bottom. The video was taken by D. Gstöhl in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

1.7 FALLING FILM EVAPORATION ON HORIZONTAL TUBES

Falling film evaporation on horizontal tube bundles is becoming an important process in refrigeration systems, in which liquid is overfeed onto the top tube of an array of horizontal tubes and evaporates as the liquid falls under the influence of gravity. The liquid flow rate thus decreases progressively from tube to tube as it evaporates. The flow of the liquid film from tube to tube is characterized by the two-phase flow regime, called the intertube flow mode here. As can be seen in some of the videos below, heat transfer is not only by conduction or convection across the film but also by nucleate boiling on the tube wall within the film. This tends to create a mist of minute droplets of liquid and in some videos the “fog” created is visible.

List of videos: (click on the one you wish to see)

Video 1.7.1: ***R-134a evaporating on array of plain tubes with partial dryout***. The video shows R-134a evaporating at 5°C (41°F) on an array of seven tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the top tube is 55000 W/m^2 (17440 Btu/h ft^2) and 30000 W/m^2 (9510 Btu/h ft^2) on the bottom tube. The flow is mostly column mode with large instabilities. The video was taken by J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the falling film heat transfer test facility, refer to: J.F. Roques, Falling film evaporation on a single tube and on a tube bundle, Ph.D. thesis, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland (2004).

Video 1.7.2: ***R-134a evaporating on array of plain tubes with nearly complete dryout***. The video shows R-134a evaporating at 5°C (41°F) on an array of seven tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The heat flux on the top tube is 96000 W/m^2 (30440 Btu/h ft^2) and 3000 W/m^2 (950 Btu/h ft^2) on the bottom tube. The flow is mostly column mode with large instabilities and then droplet flow at the bottom. The film is nearly completely dried out on the lowest tube. The video was taken by J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the falling film heat transfer test facility, refer to: J.F. Roques, Falling film evaporation on a single tube and on a tube bundle, Ph.D. thesis, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland (2004).

Video 1.7.3: ***Close up of nucleate boiling on top of tube with falling liquid film (droplet mode)***. The video shows R-134a evaporating at 5°C (41°F) on an array of tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The film flow is in droplet mode and nucleate boiling with bubbles erupting in the spreading film on the lower tube are clearly visible. The video was taken by J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the falling film heat transfer test facility, refer to: J.F. Roques, Falling film evaporation on a single tube and on a tube bundle, Ph.D. thesis, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland (2004).

Video 1.7.4: ***Nucleate boiling and dryout on top of tube in droplet mode***. The video shows R-134a evaporating at 5°C (41°F) on an array of tubes. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The film flow is in droplet mode and nucleate boiling occurs in the liquid film on the tube. Note the bubbles inside the droplets leaving the lower tube. Small liquid droplets created by the nucleate boiling process are also notable. The video was taken by J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the falling film heat transfer test facility, refer to: J.F. Roques, Falling film evaporation on a single tube and on a tube bundle, Ph.D. thesis, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland (2004).

Video 1.7.5: ***Film condensation on upper tube with nucleate boiling in film on lower tube***. The video shows R-134a condensing on the upper tube (with cooling water inside tube) and evaporating on lower tube (hot water inside tube). The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm (0.25 in.). The film flow is in droplet mode and nucleate boiling is quite evident in the liquid film on the tube. The video was taken by J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the falling film heat transfer test facility, refer to: J.F. Roques, Falling film evaporation on a single tube and on a tube bundle, Ph.D. thesis, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland (2004).

Video 1.7.6: ***Close up of nucleate boiling in film on lower tube (reverse shading)***. The video shows R-134a evaporating on lower tube with nucleate boiling in the liquid film, inverting the black and white images. The tubes are plain with diameters of 19.05 mm (0.75 in.) and the intertube spacing is 6.4 mm

(0.25 in.). The video was taken by J.F. Roques in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the falling film heat transfer test facility, refer to: J.F. Roques, Falling film evaporation on a single tube and on a tube bundle, Ph.D. thesis, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland (2004).

1.8 POOL BOILING ON HORIZONTAL TUBES

List of videos: (click on the one you wish to see)

No videos currently available.

1.9 MICROCHANNEL TWO-PHASE FLOW PHENOMENA

Two-phase flow in microchannels is a process of growing industrial importance in compact heat exchangers and electronic cooling modules. The criterion to define the threshold from macro-scale to micro-scale two-phase flow and heat transfer is still not resolved but typically at normal operating pressures is taken to be at about 1-2 mm for the internal diameter of the channel. New flow pattern maps have been proposed and others are under development to describe and identify these flow regimes. Here some representative videos are shown.

List of videos: (click on the one you wish to see)

Video 1.9.1: ***Elongated bubble (slug) flow in a 2.0 mm microchannel tube***. The video shows R-134a in a 2.0 mm (0.079 in.) internal diameter glass tube located at the exit of a microchannel evaporation test section at room temperature. Note the length to diameter ratio of the bubbles that is the characteristic of this flow. The video was taken by R. Revellin in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.9.2: ***Elongated bubble (slug) flow in a 0.5 mm microchannel tube***. The video shows R-134a in a 0.5 mm (0.02 in.) internal diameter glass tube located at the exit of a microchannel evaporation test section at room temperature. The mass velocity is 750 kg/m^{2}s (551700 lb/h ft^2) and the vapor quality is 5%. Note the length to diameter ratio of the bubbles that is the characteristic of this flow. The video was taken by R. Revellin in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

Video 1.9.3: ***Bubble flow in a 0.5 mm microchannel tube***. The video shows R-134a in a 0.5 mm internal diameter glass tube located at the exit of a microchannel evaporation test section at room temperature. The mass velocity is 1730 kg/m^{2}s (1272600 lb/h ft^2) and the vapor quality is 0.7%. Note that the bubbles are slightly smaller than the channel diameter and have not yet become elongated. The video was taken by R. Revellin in the Laboratory of Heat and Mass Transfer (LTCM) under the direction of Prof. J.R. Thome at the Swiss Federal Institute of Technology Lausanne (EPFL).

1.10 SINGLE-PHASE FLOW PHENOMENA

List of videos: (click on the one you wish to see)

No videos currently available.