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FLOODING IN COUNTER-CURRENT TWO-PHASE FLOW

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INTRODUCTION

Flooding is a phenomenon which is best described as the transition from counter-current to co-current flow. Early notice was taken of this phenomenon in the chemical engineering industry. Verschoor [58] investigated flooding in packed columns and found that there was a limiting velocity for upward flowing vapor above which liquid could not be made to flow downward in the column. The phenomenon of flooding is still important today in a number of areas. In the chemical industry a number of chemical processes rely on the counter-current flow of a gas and a liquid to provide a highly active exchange interface for both heat and mass transfer [24]. Flooding also plays an important role in the field of two-phase heat transfer since it is a limit for many systems involving counter-current flow. Practical applications of flooding limited processes include wickless thermosyphons [28,29,35,49] and the emergency core cooling system (ECCS) of pressurized water nuclear reactors [3,4,14,15,16,41,42]. The phenomenon of flooding also is involved in the behavior of nuclear reactor core materials during severe accident conditions where flooding is one of the mechanisms governing the motion of the molten fuel pin cladding [37].

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In the situation of counter-current flow, there are two fluids in motion. One of these fluids is a liquid and moves under the influence of a body force, usually gravity. The other fluid is usually a gas and moves due to a pressure gradient. In the case of gravity as the only body force, the direction of the flow of the liquid must be such that there is some component of the flow in the direction of gravity. Therefore, for purposes of classification, flooding may be divided into two categories: vertical and inclined. This survey will deal only with the category of vertical flooding. Figure 1 shows the typical topography for vertical flooding. To simply state the condition of vertical, counter-current flow, one could say that the liquid flows down while the gas flows up in the same channel.

The phenomenon of flooding may then be described as the limit point at which any increase in either the liquid or gas flow rate results in less than all the liquid flowing downward. Several other definitions have also been used to describe the flooding point. One definition is that flooding occurs at the point that any of the liquid is in upward motion, even if the overall flow is downward. Another definition is that flooding occurs when there is net flow reversal of the liquid. Still another definition that has been proposed is that flooding occurs at the onset of entrainment. Flooding may also be described in terms of the geometry of the liquid gas interface. In this case, flooding is said to occur when the liquid bridges the flow area. With these many definitions of flooding, it is not surprising that the experimental observations of flooding yield systematic differences in the measurement of the flooding point.

A further complication of the definition of flooding arises from the converse situation of transition from upward co-current flow to counter-current flow. This is sometimes called deflooding or the deflood point and does not usually coincide with the flooding point. Occasionally, especially in some analytical work, the conditions for de-flood have been analyzed as the condition for flooding.

The published literature on flooding includes both analytical and experimental work. Many of the papers include both aspects since usually all experimental data includes an attempt to explain the results. For simplicity in this survey of flooding literature, the experimental aspects of flooding will be presented first as a summary of the range of experimental data available. The analytical aspects of the experimental works will be included with the purely analytical works.

Figure 1.

EXPERIMENTS

Flooding has been studied experimentally in a variety of geometries, with several sets of fluid pairs, and over a range of flowrates for both liquid and gas. The most common geometry studied is that of the tube of circular cross section. Other geometries include rectangular channels, annuli, and multiple channels such as those formed by the fuel pins in a nuclear reactor. The most common fluid pair is air and water with steam and water second. Other fluids include glycerol, glycerol and water solutions, isopropyl alcohol, methyl alcohol, n-neptane,

ethylene glycol, diethylene glycol, aqueous sec.-octyl alcohol, silicon oil, and water with various surfactant agents. Nitrogen has been also used as the gas phase. The data collected has included: liquid holdup; pressure drop; average liquid film thickness; liquid surface characteristics such as disturbance wave and ripple height, velocity, and speed; and the flow rate of both liquid and gas at the flooding point and entrainment.

The experimental data is organized first by the geometry of the test section. The second level of organization is by the fluid pair. Finally, the experiments are presented in chronological order.

Experiments in tubes

The air-water flooding in tubes has been studied over a wide range of diameters and lengths.

Wallis [59,60], Hewitt and Wallis [27] and Hewlitt, Lacey, and Nichols [26] studied flooding in a 31.8 mm ID acrylic resin pipe. The water was introduced through a porous bronze sinter section and removed by a second sinter section [27]. Test sections lengths of 0.23 m, 0.46 m, 0.91 m, 1.82 m, and 3.65 m were used [26]. The water flow rate varied from 2.5 g/s to 75 g/s. The air flow rate varied from zero to 11.4 g/s. The experiment was performed at pressures of 137 kPa, 275 kPa, and atmospheric. The data recorded included air and water flow rates, pressure drop, system pressure, and film thickness using a conductance probe. High speed photography at 100 to 250 frames per second was used to study the liquid film [27]. Liquid film thickness was measured using a fluorescent dye irradiated by monochromatic light [26]. The fluorescence was separated from reflected incident light by a spectrometer.

Clift, Pritchard, and Nedderman [12] studied flooding in a 31.8 mm ID, 3.7 m long tube. with a 76 mm long bronze sinter feed section in the middle of the tube. The velocity of the air varied from 8.25 m/s to 9.50 m/s. The water volumetric flow rate varied from 1 cm³/sec to 52 cm³/sec. In addition to flow rates, the pressure drop in the tube was also measured. Waves were visually observed as gas velocities approached the flooding point. As the flooding point was almost reached, the pressure drop increased sharply and the waves on the film became sufficiently large to bridge the tube. The bridges were broken by the air flow and the resulting drops were carried up by the air stream. Further increase in either the gas or liquid flow caused an increase in both the pressure drop and the height of the liquid slugs above the liquid entrance. The liquid below the entrance was less chaotic after flooding. Still further increase (after flooding) caused a slight decrease in the pressure drop.

Diehl and Koppány [17] studied flooding with water and air in tubes with diameters of 15.8 mm, 26.6 mm, and 52.5 mm. The flooding point was determined by noting the gas velocity at which there was a large increase in entrainment, and by checking the pressure drop increase as gas flow was increased. The results were reported only in terms of gas velocity and entrainment loads.

Pushkina and Sorokin [44] studied both flooding and liquid film breakdown. Flooding was defined as the onset of entrainment with some motion of a part of the liquid upward. This included cases in which the entrained droplets were deposited on the wall above the water injection point and flowed downward in a film with no exit of fluid from the top of the tube. Film breakdown was defined as the point at which liquid downflow ceases and all of the liquid is carried upward. Two different sets of apparatus were used in the study. One of these consisted of a 309 mm ID tube with a porous liquid feed insert. The porous section was 210 mm with a 3.75 meter section above and a 2.5 meter section below giving a total test section length of 6.46 meters. The second apparatus consisted of a set of varying diameter tubes which were top fed from a reservoir through a funnel. The air was introduced into a lower plenum. Tubes with an interior diameter of 6.2 mm, 8.8 mm, 9.0 mm, 12.2 mm, and 13.1 mm were used. The length of the tubes varied from 0.5 meter to 0.8 meter. The water flow rate was the minimum which would continuously wet the tube around its entire circumference. For the porous feed apparatus, the air velocity was adjusted to produce both flooding and film flow reversal. For the top feed apparatus, the air velocity was adjusted to produce film flow reversal. The velocity of the air was in the range 14 m/s to 16 m/s. Measurements were made of the water and air flow rates.

Wallis and Makkenchery [66] investigated the transition region between the flooding point and upward co-current flow. In this region, there is no net film motion and hence the phenomenon is sometimes called the "hanging film" phenomenon. The experiments were carried out in tubes 6.35 mm and 140 mm in diameter. Liquid entered from the top of the tube either by overflowing a weir or by running down a tapered funnel. Measurements were made of the air and water flows.

Kusuda and Imura [35] performed experiments to determine the critical heat flux in an open two-phase thermosyphon. They confirmed that dryout occurs only with counter-current annular two-phase flow as a result of flooding rather than local film boiling. One tube was 1 meter in length and 28.4 mm in diameter. Other tubes were 0.2 and 0.3 meters in length and 10.7 mm in diameter.

Wallis and Kuo [67] performed flooding designed to study the interfacial effects of flooding. One experiment involved measuring

the height to which water could be supported over the lip of a tube with air exiting the tube. Tubes of the following diameters were used: 6.4 mm, 19 mm, 31.2 mm, 38.2 mm, 63.5 mm, 113 mm, and 145 mm. Measurements were made at the water level and air flow. A second experiment involved the behavior of a toroidal liquid ring hanging around the inner wall of a glass tube with gas flow. The liquid ring was initially formed by allowing the liquid to build up over a teflon inset which formed a step in the tube.

Dukler and Smith [23] performed flooding studies in a 50.8 mm tube with very carefully controlled liquid and gas entry conditions. Their apparatus consisted of a 3.96 m long plexiglass tube with a 0.1 m porous, sintered metal inlet located at axial midplane. The gas entrance consisted of 304 mm I.D. section with a 50.8 mm nozzle for gas entry and an expanding taper on the main tube to pull the liquid film away from the stream of entering gas. Data was collected for liquid Reynolds numbers of 329.1, 822.8, 1645.5, and 3291.0 respectively. The superficial gas velocities varied from 6.5 m/s to 15.2 m/s and corresponded to gas Reynolds numbers from 22,250 to 59,971. The data recorded included liquid and gas flow rates. Pressure level and film thickness was measured at four axial locations. The film thickness was measured using conductivity probes. At the two lower liquid flow rates, waves on the falling film changed only slightly in appearance with increases in air flow. Just below the flooding point, fluctuations were noted in the film at both the air entrance and just below the water entrance. A small increase in the air flow caused these fluctuations to spread over the entire film creating a highly agitated surface. The film then climbed and entrainment took place simultaneously. For the higher water flow rates, droplets were observed striking the surface of the tube above the water entrance with gas flow just below the flooding point. The droplets formed a very thin film which ran down the tube. A small increase in the air flow, caused a disturbance in the liquid film 150 mm below the water entrance. At the flooding point, the upper section of the tube filled with an aerated liquid in churn flow. A net upflow of liquid resulted.

Imura, Kusuda, and Funatsu [28] studied flooding in 1 meter long acrylic resin tubes with varying diameters. The ranges of parameters studied for the air and water system are given in Table 1. The water was introduced over a bell mouth at the top of the tube. Air and water flow rates and pressure drop data were recorded. The flooding point was determined by visual observation and increase in the pressure drop.

TABLE 1. Range of Parameters studied by Imura et al [28]

Tube ID (mm)	Liquid Properties		Gas Properties	
	superficial flow (mm/s)	Re	Velocity (m/s)	Re (10 ³)
11.2	37.1-532.	145-1820	1.62-7.17	1.62- 7.17
16.0	17.3-470.	77-2030	4.65-8.93	4.39- 9.14
21.0	49.1-278.	316-1520	4.45-7.94	5.68-10.2

Suzuki and Ueda [55] investigated flooding in transparent acrylic resin tubes of 10 mm, 18 mm, and 28.8 mm diameters. The lengths of the 10 mm and 18 mm ID tubes used were 0.5, 1.0, 1.5, and 2.0 meters. The lengths of the 28.8 mm tubes were 0.59, 1.54, and 1.83 meters. The water was introduced through a sintered section of all. The water flow rate was varied to provide liquid Reynolds numbers from 240 to 8180. Air flow was ranged to cover both the flooding point and the limit of upward co-current flow. Transition points were recorded for both increasing and decreasing gas flow. Measurements were made of the liquid and gas flow rates. The waves on the liquid film were studied by using a contact probe to determine wave height and by using high speed photography to determine wave velocity.

Diehl and Koppany [17] performed single-component condensation studies in a 8.1 mm tube.

Wallis et al. [65] reported the results of experiments in a transparent 50.8 mm pipe. The pipe was 1.5 m in length with a large upper plenum (0.6 m high) and a large lower plenum (0.7 m high). The system was a top flood arrangement with water collection in the upper plenum. Both "square" and rounded transitions were used at both the upper and lower end of the pipe. Water at temperatures from 277 K to 372 K was supplied to the upper plenum through a feed ring near the bottom of the plenum. Saturated steam at a pressure of 41 kPa (gage) to 90 kPa (gage) was supplied to the lower plenum below a demister and turbulence suppressor. Steam was supplied at flow rates up to 23 g/s. The experiments were conducted in both steam first and water first sequences. Measurements were made of steam flow, water inlet flow, water flow to the lower plenum, inlet steam and water temperature, and upper and lower plenum temperatures and pressures.

English et al. [24] investigated two phase flow in a flooded, updraft, partial condenser. The apparatus consisted of a 1.8 m long, 19 mm diameter tube in a condenser. The fluid was n-propyl alcohol which entered a calming section at the lower end of the tube as a vapor. Various fractions of the vapor were condensed and

exited the tube as condensate at the bottom and as entrained droplets at the upper end. The parameters measured included: gas mass flow rate; entrainment mass flow rate; liquid to gas fraction, and pressure drop. The gas flow rate varied from 3.39 Kg/s. m² to 13.56 Kg/s. m². Liquid to gas fractions from 0.2 to 0.8 were studied. An additional study addressed the effect of tapers (diagonal cuts across the entrance). Tapers of 0, 30, 45, and 75 degrees were studied.

Cliff, Pritchard, and Nedderman [12] also studied flooding using solutions of glycerol and water as shown in Table 2. With the more viscous solutions, waves were observed in the lower part of the tube with low or zero air flow. Increase in air flow caused the point of inception of the waves to move upward until the entire portion of the tube below the liquid entrance was wavy.

Diehl and Koppany [17] studied flooding using a hydrogen and diesel oil system in tubes with diameters of 16.8 mm, 18.7 mm, and 23.7 mm.

TABLE 2. Range of Glycerol/water mixtures [12]

Solution (%Glycerol %Water)		Viscosity (Pa-s .10 ⁻³)	Density (g/ml)	Surface Tension (N/m)
82	18	82.5	1.21	0.0650
77	23	46.0	1.20	0.0658
70	30	23.4	1.18	0.0664
59	41	10.4	1.15	0.0680
25	75	2.18	1.06	0.0702
--	100	1.32	1.00	0.0720

Kusuda and Imura [35] used a number of fluids in their thermosyphon. Ethyl-alcohol, nandmal-hexane and carbon-tetrachlandide were used.

Imura, Kusuda, and Funatsu [28] investigated flooding with ethyl-alcohol, ethylene-glycol, and n-Heptane. The tubes were 11.2 mm, 16.0 mm, 21.0 mm and 24.2 mm in diameter. All of the tubes were 1 meter in length. The range of the experimental parameters are given in Table 3.

Wallis and Kuo [67] investigated the conditions of the "hanging film" phenomenon using silicon oil and air.

Suzuki and Ueda [55] studied flooding using aqueous glycerol solutions and aqueous sec.-octyl alcohol solutions in 18 mm and 28.8 mm tubes. Air was used as the gas in all cases. The glycerol solutions allowed the viscosity of the fluid to be varied while maintaining an almost constant surface tension. The liquid Reynolds numbers varied from 7 to 3620. Table 4 gives the

viscosities and surface tension of the various solutions and the dimensions of the apparatus used. The sec.-alcohol solutions allowed the surface tension to be varied while maintaining a constant viscosity equal to that of water. Table 4 give the data concerning the range of surface tension, viscosity and liquid Reynolds number.

TABLE 3. Parameters studied by Imura et al [28]

Tube ID (mm)	Liquid Properties		Gas Properties	
	Superficial Flow (mm/s)	Re	Velocity (m/s)	Re (10^{-3})
Ethyl-alcohol				
11.2	13.9-489.	24.- 971	2.84-6.44	1820- 4810
11.6	6.0-552.	15 -1580	2.59-7.70	2410- 8400
21.0	11.0-389.	36 -1380	3.71-7.32	3710- 7320
Ethylene-glycol				
11.2	26.1-629.	5.7- 152	1.65-5.67	810- 3710
16.0	10.8-840.	2.7- 303	1.10-8.00	900- 7810
21.0	9.5-632.	2.7- 303	1.75-8.48	1830-11400
24.2	12.7-539.	3.5- 182	2.43-7.90	3370-11700
n-Heptane				
11.2	20.4-393.	101 -2080	0.86-4.60	560- 3240
16.0	14.3-488.	104 -3750	0.56-6.13	510- 6070
21.0	7.8-415.	62 -3610	0.80-11.9	800-11900
24.2	8.1-375.	87 -3610	1.42-7.72	2070-12100

TABLE 4. Parameters studied by Suzuki and Ueda [55]

Viscosity (Pa.s .10 ⁻³)	Surface Tension (N/m)	Liquid Reynolds Number	
		18 mm tube	28.8 mm tube
Water			
0.9	0.068	390-5240	820-8180
Aqueous glycerol solutions (308K)			
2.1	0.056	140-2840	320-3620
5.1	0.053	30-1030	80-1200
10.0	0.053	25- 380	50- 510
24.0	0.053	7- 100	35- 140
Aqueous sec.-octyl alcohol solutions (298 K)			
0.9	0.055	390-3280	820-4010
0.9	0.047	390-3930	820-8180
0.9	0.037	390-2620	820-8180

Grolmes, Lambert, and Fauske [25] investigated flooding in a nitrogen and water system. The tube diameters ranged from 4 mm to 25 mm ID. Length to diameter ratios from 10 to 100 were studied. Measurements included gas and liquid flow rates and pressure drop. The onset of flooding was determined by both visual observation and pressure drop. For the larger tubes (6, 13, 25 mm), the liquid film waviness grew steadily in amplitude over the entire length of the tube as gas velocity increased. However, for the 4 mm tube, the transition to flooding was described as "a closing of the gas annulus by a single wave crest." Intermittent slug flow developed following the flooding transition.

Flooding in annuli

Stainthorp [52,53] investigated both co-current and counter-current air-water flow with emphasis on the effect of the air flow on the wave properties of the falling liquid film. The test section consisted of a tube 34.5 mm ID and 0.7 m long. A second 19.8 mm OD tube concentrically mounted formed an annular region and provided a housing for photo-transistors located on the tube axis. Since the inner tube was approximately half the diameter of the outer tube and water was introduced only on the surface of the outer tube, the geometry could also be considered that of a tube with a "probe". It is considered annular here for comparison with other work done in annular geometries which also have similar diametrical ratios. Water was introduced through the outer wall by using a 0.1 m long section of porous ceramic tubing of the same bore as the tube. Liquid flow was adjusted to provide liquid Reynolds from 10 to 180. Air velocities ranged from zero to 10 m/s. Measurements were made of the air and water flow rates. Film thickness and wave velocity was measured using a 1.5 g/l solution of Nigrosine and the change in light transmittance was measured by a pair of photo-transistors illuminated by a pair of 0.25 mm diameter beams 16.5 mm apart.

Naff and Whitbeck [40] investigated counter-current flow in an annular geometry using a plexiglass vessel with aluminum inserts to simulate the reactor core barrel and downcomer region of a pressurized water reactor (PWR). Figure 2 shows the geometry. Tests were conducted for radial gaps of 9.4 mm, 12.4 mm, and 16.0 mm with downcomer lengths of 0.15 m, 0.63 m, 0.86 m, and 1.72 m. The gas was introduced into the top of the "core barrel" and entered the lower plenum through bottom perforations. Water entered through a nozzle located near the top of the vessel wall and the air-water mixture exited through another nozzle located 180 degrees opposite. The incoming liquid velocity varied between 0.54 m/s and 2.2 m/s. The gas velocities were adjusted to obtain flooding by controlling the exit pressure so that a constant lower plenum pressure could be maintained. Tests were conducted at a system pressure of 69 kPa and 206 kPa (gage) to provide gas densities of 16 and 32

kg/m³ Measurements were made of the air and water flow rates and the filling rate of the lower plenum. Visual observations were also made.

A similar set of experiments were performed at Battelle Columbus Laboratories by Segev and Collier [48]. In these experiments a 2/15 scale model of a PWR plenum was used. Table 5 shows some of the physical dimensions of both the 2/15 scale model and a 1/15 scale model as well as the dimensions of the PWR.

Figure 2.

TABLE 5. Geometric Dimensions used By Segev and Collier [48]

Reference Geometry	1/15 scale	2/15 scale	PWR
Annular Gap, mm	15.	31.	254.
Downcomer length, m	0.41	0.82	5.33
Average Circumference, m	0.918	1.845	12.85

The 1/15 scale model data was supplemented by data from experiments at Creare [2,3,4,5,14]. In addition to steam water experiments, some experiments with air and water were performed for comparison. The resultant data was used to evaluate the effect of phase change. Various length core barrels were used to create different length downcomers.

Ueda and Suzuki [57] studied flooding in annular geometry with the flow on the inside wall of the annulus. The inner diameter of the annulus was 10.0 mm. The outer shroud diameters were 28 mm, 35 mm, and 40 mm which produced annular gaps of 9.0 mm, 12.5 mm, and 15.0 mm, respectively. The test section length was 1 meter. Liquid was supplied through a 80 mm long sintered bronze section at the top of the inner wall. The liquid flow rates varied from 3.3 to 16 ml/s. This corresponded to liquid film Reynolds numbers of 472 to 2360. The air velocity varied from 5.5 to 9 m/s. Measurements were made of the liquid and gas flow rates. The maximum liquid film height was measured using a contact probe at locations 0.3 m, 0.6 m, and 0.9 m below the sinter section. Single phase air velocity distribution was measured using a pitot tube. Visual observations were also made.

Kusuda and Imura [35] investigated flooding in annular geometries by using inserts in their thermosyphon to produce an annular, open, top flooded configuration. Inserts of diameter 12.1 mm, 19.1 mm, and 25.2 mm were inserted into the 28.4 diameter, 1 meter long, tubes to produce annular gaps of 8.2 mm, 4.7 mm, and 1.6 mm, respectively. Inserts were also used in the 0.3 meter long, 10.7 mm ID tubes. Inserts of 6.5 mm and 8.0 mm produced annular gaps of 2.1 and 1.4 mm, respectively.

Crowley, Block, and Cary [14] investigated flooding in a 1/15-scale PWR downcomer geometry. This experiment was aimed at predicting lower plenum filling rates in postulated reactor accidents. As a result, flooding was only one of the effects studied. Other effects included lower plenum voiding, cold leg steam, and superheated downcomer walls. The experimental facility consisted of a thick walled steel vessel. Variable core barrels were used to provide annular gaps of either 12.7 mm or 25.4 mm. The water was injected to simulate an emergency core cooling system (ECCS). Water flow up to a maximum of 6.3 l/s per cold leg was supplied. The maximum total water flow was 18.9 l/s. The total available steam flow was 1.4 kg/s. The water injection temperatures varied from 289 K to 322 K. The steam injection temperature varied from 373 K to 444 K. System operation pressure was 0.86 MPa. Measurements were made of the lower plenum filling rate, pressure drop, and flow rates.

Kusuda and Imura [35] used inserts with a few combinations of other fluids. Ethyl-alcohol was used in the 28.4 mm ID thermo-

syphon with inserts of 12.1 mm, 19.1 mm and 25.2 mm to produce annular gaps of 8.2 mm, 4.7 mm, and 1.6 mm, respectively. Normal-hexane was used with 6.5 mm and 8.0 mm diameter inserts in the 10.7 mm ID, 0.3 meter long tube to produce annular gaps of 2.1 and 1.4 mm.

Ueda and Suzuki [57] used an aqueous sec.-octyl alcohol solution in annular flooding studies. The tube diameters for these studies were the same as their water-air studies, 10 mm ID, 28 mm, 35 mm and 40 mm OD.

Simulated annular geometries

Crowley [15] investigated steam and water counter current flow in a 1/30 scale, flat-plate plastic model of a pressurized water reactor downcomer. The simulated annulus consisted of two 305 mm x 457 mm polycarbonate plates separated by a 9.5 mm gap. The water entrances were 43 mm holes that bridged the annulus. The water was supplied at rates up to 940 g/s at temperatures of 286 K, 311 K, and 333 K. The steam flow was in the range of 15 to 105 g/s at atmospheric pressure and a temperature of 375 K to 376 K. The variables measured included steam and water flow rates and steam pressure in the supply barrel up to a maximum of 13 kPa.

Other geometries

Verschoor [58] investigated the limiting velocity of vapor in packed columns.

Shearer and Davidson [51] investigated the standing wave generated by upward flow of air through an orifice with a rod with downward flowing water film in the center of the orifice. Although not flooding in the classical sense, this counter-current flow situation was used to study the forces on large disturbance waves which are often associated with flooding. A 25.4 mm diameter rod was used. The orifice was 38.1 mm in diameter on the upper side and expanded to 68.3 mm on the lower side of a 4.8 mm thick plate. The air and water rates were varied over a very small range of stability. If the air rate decreased slightly, the wave disappeared. If it increased slightly, droplets were ripped off the crest of the wave. If the water flow rate was reduced slightly, the tube did not wet fully. If it increased slightly, rippling occurred and made the wave unstable. Once a stable wave had been produced, it was photographed and a brass model of the wave was constructed and fitted with internal pressure taps. By using the brass replica, it was possible to obtain pressure readings at the interface.

Ueda and Suzuki [57] performed flooding experiments in simulated nuclear reactor rod bundles of three and four rods. All

the rods were 10.0 mm in diameter and 1.0 meter in length with a sintered section for fluid entry at the top. It was possible to vary the amount of liquid to each rod independently. The set of three or four rods was contained in one of a set of shrouds of diameters either 28 mm, 35 mm, or 40 mm. This allowed a variety of rod to rod spacings.

Naitch, Chino, and Kawabe [41] studied the restrictive effect of ascending steam on falling water during top spray emergency core cooling in a rectangular array of fuel pins. The test section consisted of 64 rods, 12.5 mm in diameter, arranged in a square lattice with 16.3 mm pitch. The length of the test section was 4.508 meters. Steam was injected into the lower plenum to simulate generation of steam in a BWR. Water with various degrees of sub-cooling was injected in the top of the test section. Therefore several effects were studied in addition to flooding. These effects included condensation and type of water injection nozzle. The flow rate of steam supplied to the test section varied from 43 to 83.3 g/s. The spray water rate varied from 117 to 1033 g/s. Temperature of the spray water varied from 300 K to 370 K. Measurements were made of the water and steam flow rates. The amount of condensation was based on a separate set of measurements with steam only and no spray.

ANALYTICAL METHODS

The phenomenon of flooding has not yet yielded to a complete analytical explanation. The various attempts at explanation and prediction of flooding fall under three general categories: empirical; semi-empirical or semi-analytic (depending on point of view); and analytical.

Empirical correlations

Purely empirical correlations for flooding generally have a weak physical basis and are no longer in wide use.

English et al. [24] developed a correlation for gas and liquid flow in a vertical upright partial condenser. A total of 56 flooding determinations were plotted as a function of the liquid to gas ratio. The other variables, tube diameter, liquid density, surface tension, gas viscosity, liquid viscosity, and the angle of the tube taper, were combined using fractional exponents to produce minimal scatter on a log-log plot. The best straight line was then fitted through these points and the slope calculated to determine the fraction exponent for the liquid to gas (L/G) ratio. The results were rewritten in terms of the maximum allowable gas superficial mass flow rate. The equation given below is recursive in the gas superficial mass flow rate.

$$j_g = 1550 \left[\frac{D^{0.3} \rho_l^{0.46} \sigma^{0.9} \rho_g^{0.5}}{\mu_l^{0.14} (\cos \theta)^{0.32} (j_l/j_g)^{0.07}} \right] \quad (1)$$

where

D = tube diameter, inches

θ = taper angle

j_l, j_g = superficial velocity of liquid and gas, ft/s

The weak dependence on G requires a one or two time iteration.

Diehl and Koppány [19] developed a correlation of the form:

$$V_g = F_1 (j_l/j_g)^{-0.25} (\sigma/\rho_g)^{0.5} \quad (2)$$

where

$$F_1 = \begin{cases} (80D/\sigma)^{0.4} & 80D/\sigma < 1.0 \\ 1.0 & 80D/\sigma > 1.0 \end{cases}$$

V_g = gas velocity, ft/s

The determination of the F_1 constant is based on a equation for the critical diameter presented in the paper. This equation, however, is not consistent in units and a mixed form of units persists throughout the paper. Therefore, this correlation is suspect as to the correct units.

Semi-empirical correlations

These correlations include the Wallis Correlation and the Kutateladze Correlation. Both of these correlations enjoy wide use as predictive methods and are often used without regard to the limits of their data.

The approach used in the Wallis [63,64] correlation is to reduce the superficial velocity of both the gas and the liquid to its respective dimensionless velocity. The dimensionless velocities are:

$$j_g^* = \frac{\rho_g^{1/2} j_g}{[gD(\rho_l - \rho_g)]^{1/2}} \quad (3)$$

and

$$j_l^* = \frac{\rho_l^{1/2} j_l}{[gD(\rho_l - \rho_g)]^{1/2}} \quad (4)$$

The dimensionless velocities are then combined in the form:

$$j_g^{*1/2} + m j_l^{*1/2} = C \quad (5)$$

The value of the constants are then fitted to the data. The value of C varies from 0.88 to 1.00 when m=1.

Kutateladze [36] developed a correlation similar to the Wallis correlation. The liquid dimensionless velocity is of the form:

$$K_l = \rho_l^{1/2} j_l / [gg_c \sigma (\rho_l - \rho_g)]^{1/4} \quad (6)$$

The gas dimensionless velocity is:

$$K_g = \rho_g^{1/2} j_g / [gg_c \sigma (\rho_f - \rho_g)]^{1/4} \quad (7)$$

The final form of the equation is:

$$K_g^{1/2} + m K_l^{1/2} = C \quad (8)$$

The Wallis and Kutateladze correlations are not complete solutions of the flooding phenomenon, but rather are usable tools for finding solutions to specific cases without knowing the complete solution. Therefore, it is not surprising that in a given case, one correlation may perform better than the other when compared to experimental data. Such differences should always be understood in the context of the relation of the specific problem under study to the ranges and limitations of each of the correlations.

Pushkina and Sorokin [44] emphasized the differences between the Wallis and the Kutateladze correlations with two sets of experiments. One set was performed in a 309 mm tube as described previously. The other set of experiments was performed in a series of small tubes with internal diameters of 6.2 mm, 8.8 mm, 9.0 mm, 12.2 mm, and 13.1 mm. All of the small tubes used a funnel as a top liquid feed. Both sets of experiments investigated flooding at the lower limit of liquid flow on the flooding curve (i.e. the point just above film breakdown). The analysis focused on determining a critical air velocity for flooding. The results presented show a critical velocity for air of 14 m/sec to 16 m/sec. In the analysis, an arbitrary 0.2 mm correction for film thickness was used for all tubes less than 12.2 mm. The results do

show that a decrease in critical velocity occurs even when using the film correction. If the smaller and larger tubes had been corrected the same, there would have a slight slope to the critical velocity versus tube diameter curve. The Wallis correlation predicts a straight line but with a positive slope when applied to the same cases. Pushkina and Sorokin claimed this data that demonstrated the superiority of the Kutateladze correlation to the Wallis correlation.

Wallis and Makkenchery [66] offered a partial explanation of the differences in the Wallis and the Kutateladze correlations regarding the data of Pushkina and Sorokin. They emphasized that the Wallis correlation was originally based on data taken in tubes ranging from 12.7 mm to 50.8 mm. They stated that since the Kutateladze correlation contained no characteristic dimension of the apparatus, that it would be best suited for large diameter tubes provided the liquid film remained thin. For small tubes surface tension effects would be important. To support this claim, Wallis and Makkenchery presented data showing the difference in velocity required to support a hanging film compared to that required for flow reversal was a factor of two greater in small tubes compared to large tubes. Wallis and Makkenchery proposed that the range of surface tension effects could be expressed in terms of a dimensionless tube diameter by using the Bond number.

$$D^* = D[g(\rho_l - \rho_g)/\sigma]^{1/2} \quad (9)$$

In addition, the critical dimensionless gas velocity used by Wallis [83] and that used by Pushkina and Sorokin [61] could be related as the square root of the Bond number.

An additional factor, not mentioned by either Pushkina and Sorokin or Wallis and Makkenchery was the method of fluid entry used in Pushkina and Sorokin's experiments. The large 309 mm tube used an extended midsection fluid entry consisting of several thousand drilled holes simulating to the porous entries used by many researchers. Flooding in this large tube was best represented by the Kutateladze correlation as expected. The smaller tubes used an overflowing funnel liquid entrance. Thus, there was no rigid wall supporting the reservoir of fluid in the event that it was above the lip of the funnel. Any instability created in this region may be transferred down the tube. The Kutateladze correlation is based on a physical geometric parameter representative of a wavelength similar to a Taylor instability rather than a geometric parameter like the Wallis correlation. Therefore, the Kutateladze correlation may have better represented the effects of any instabilities generated. This is an excellent example of considering all of the the varying parameters which may influence the applicability of a specific correlation to a given situation.

Alekseev et al. [1] developed a correlation based on the Kutateladze, Froude, Weber, and Galileo numbers.

$$K_g = 1.13 Fr^{-0.20} We^{-0.21} Ga^{-0.09} \quad (10)$$

where

$$Fr = \frac{Q_L (\rho_L - \rho_g)^{3/4}}{g^{1/2} \sigma^{3/4}} \quad (11)$$

$$We = \frac{\sigma}{(\rho_L - \rho_g) D^2} \quad (12)$$

$$Ga = \frac{g \sigma^{3/2}}{U_L^2 (\rho_L - \rho_g)^{3/2}} \quad (13)$$

Q_L = mass flow/wetted perimeter

Grolmes et al [25] use the Nusselt solution for average film thickness in the falling film without gas flow as a basis to calculate the critical gas velocity for flooding.

$$V_g = 1.15 \left(\frac{\rho_L}{\rho_g} \right) \left[\frac{g \delta_N}{0.006 + \frac{200 \delta_N^2}{(\mu_L/\mu_R)^{0.44}}} \right]^{1/2} \quad (14)$$

where

μ_L/μ_R = ratio of liquid viscosity to that of water

and δ_N is the Nusselt film thickness, calculated as follows:

$$\delta_N = (3 Q_L \frac{\mu_L}{\rho_L g})^{1/3} \quad (15)$$

Imura et al. [28] also produced a correlation based on Nusselt's film thickness solution.

$$\frac{j_g}{j_L} \left(1 + \frac{j_L \rho_L S_L}{j_g \rho_1 S_1} \right) = \frac{S_L}{S} \frac{1}{L} \left(\frac{\rho_L \sigma}{\delta_N} \right) \left(\zeta - \frac{1}{R/\delta_N - 1} \right)^{1/2}. \quad (16)$$

where

$$S = \pi D^2/4 \quad (17)$$

$$S_1 = \pi D \delta_N (1 - \delta_N/D) \quad (18)$$

$$S_g = (\pi D^2/4)(1 - 2\delta_N/D)^2 \quad (19)$$

$$z = 0.046 \left(\frac{d^2 \rho_l g}{\sigma_N} \right)^{0.3} \left(\frac{\mu_l}{\mu_g} \right)^{0.12} \quad (20)$$

Suzuki and Ueda [55] used four nondimensional groups to form a flooding correlation. The Froud number,

$$Fr \equiv [\rho_g (V_g + V_L)^2 / \rho_L g y_i]^{1/2} \quad (21)$$

where $\rho_g (V_g + V_L)^2$ represents the kinetic energy of the gas based on relative motion of the phases, is defined in terms of the other three nondimensional groups.

$$Fr = C_1 \log_{10} [Re_L^{-1/3} \left(\frac{\rho_L g D^2}{\sigma} \right)^{1/4} \left(\frac{\mu_g}{\mu_L} \right)^{2/3}] + C_2 \quad (22)$$

The modified surface tension σ' is defined as:

$$\sigma' = \sigma_N + 1.5|\sigma - 0.05| \text{ N/m} \quad (23)$$

Crowley et al. [14] based a correlation on the Wallis correlation but modified it to account for condensation of steam. This represents an extension of the purely hydrodynamic aspects of flooding to cases involving heat transfer and phase change. However, since the steam-water system is of much importance, it is included in this summary. The gas dimensionless velocity is modified as follows:

$$J_g^* = J_{gc}^* - f(T_{\text{sat}} - T_f) \left(\frac{c_p}{h_{fg}} \right) \left(\frac{\rho_f}{\rho_g} \right)^{1/2} J_{f,\text{in}}^* \quad (24)$$

where J_g^* refers to the Wallis equation, J_{gc}^* is the value with condensation, and f is a measure of the condensation efficiency

$$f = \left(\frac{P_{LP}}{P_{\text{atmos}}} \right)^{1/4} \left(\frac{1}{1 + 30J_{f,\text{in}}^*} \right) \quad (25)$$

The m and C constants in the Wallis equation are then determined experimentally to be:

$$m = \exp (-5.6(J_{f,in}^*)^{0.6} \quad (26)$$

$$C = 0.32 \quad (27)$$

A number of correlations have been developed for specialized geometries. Many of these geometries apply to those found in either boiling water reactors or pressurized water reactors.

Sun [54] correlated data for both the tieplates and bottom side-entry orifices of boiling water reactors. The Kutateladze correlation was used, but a different set of constants was established for each case. For the tieplates with three different methods of steam injection, the constant $m=1$, but the constant C depended on method of steam injection. For the capped steam sparger.

$$(K_g)^{1/2} + (K_f)^{1/2} = 1.89 \pm 6\% \quad (28)$$

For the clarinet steam sparger.

$$(K_g)^{1/2} + (K_f)^{1/2} = 2.10 \pm 13\% \quad (29)$$

For the lower tieplate steam sparger.

$$(K_g)^{1/2} + (K_f)^{1/2} = 2.07 \pm 8\% \quad (30)$$

For the bundle side-entry orifices, the constant, $m=0.59$ and the constant, C, was calculated in terms of the Bond number.

$$K_g^{1/2} + 0.59 K_f^{1/2} = 2.14 - 0.0080 D^* \quad (31)$$

Dilber [18] presented a correlation based on counter-current injection of water above a perforated plate. He defined a dimensionless flow which combined features from both the Wallis and Kutateladze correlations. The correlation is in the form:

$$H_g^{*1/2} + H_f^{*1/2} = C \quad (32)$$

where the dimensionless flow, H, is defined as :

$$H_{f,g}^* = [\rho_{f,g}/gw(\rho_f - \rho_g)]^{1/2} j_{f,g} \quad (33)$$

and w is :

$$w = D_h^{(1-\alpha)} [\sigma/g(\rho_f - \rho_g)]^{\beta/2} \quad (34)$$

$$\beta = \tanh \left[\frac{2\pi D_h}{t_p} (A_h/A_t) \right] \quad (35)$$

A_h/A_t = perforation ratio

D_h = hole diameter

t_p = plate thickness

The use of the hyperbolic tagential function, a , results is a smooth transition between the Wallis ($\beta=0$) and Kutateladze ($\beta=1$) correlations. The value of C is given in terms of the Bond number.

$$C = 1.07 + 4.33 \times 10^{-3} D^* \quad (36)$$

where

$$D^* = n\pi D_h [g(\rho_\ell - \rho_g)/\sigma]^{1/2} \quad (37)$$

Analytical models

Flooding may never yield to a purely analytical approach due to the statistical nature of the turbulence present. However, analytical approaches, even with their often gross simplifications, provide insight and direction into the process.

Richter [45] proposed a correlation which is an extention of the Wallis correlation in an attempt to resolve the differences between the Wallis and the Kutateladze correlations. The approach used by Richter is to set up control volumes for both entire pipe and for the gas bounded by the interface. This allowed him to eliminate the pressure drop by combining the equations for each control volume.

$$\frac{4 \tau_w}{D} + \frac{4 \tau_i}{D\sqrt{\alpha}} = (\rho_\ell - \rho_g)g(1 - \alpha) \quad (38)$$

τ_w = wall shear

τ_i = interfacial shear

α = void fraction

The three remaining unknowns are the wall shear stress, τ_w , the interfacial shear, τ_i , and the void fraction, α . The wall and interface shear is transformed to wall and interface friction factors, respectively. The wall and interfacial friction factors

are then related through Wallis' correction for wavy annular flow [62].

$$f_i + f_w \left(1 + 300 \frac{\delta}{D}\right) \quad (39)$$

f_w = wall friction factor

f_i = interfacial friction factor

δ = film thickness

The above is in terms of the film thickness and pipe diameter. The void fraction can also be expressed in the same terms. Therefore, it is possible to eliminate one variable. Experimental data by Wallis regarding the ratio of d/D for the case of little interfacial shear is used to arrive at a wall friction factor of $f_w = 0.008$. At this point, Richter makes several assumptions concerning the large disturbance waves that have been observed prior to the onset of flooding. First, the wave is assumed to have a semicircular shape. Second, it is assumed that the pressure difference between the base and crest of the wave is due to the dynamic head of the gas flow. Third, the mechanism of flooding is considered to be total entrainment with onset of entrainment coincident with flooding. Using this assumption, stability requirements on the wave require the dynamic head of gas flow to be less than or equal to the ratio of wave height to surface tension. The final form of the correlation is of the form:

$$\frac{f_w}{4} D^3 J_g^{*6} J_L^{*2} - f_w D^* J_g^{*4} + 150 f_w J_g^{*2} = 1 \quad (40)$$

Maron and Dukler [39] present an analysis based on the structure of the film flow. Additional details of the analysis can be found in a report in which Dukler assumes that the liquid inlet is located below the top of the test section so that a liquid may exist both above and below the inlet depending on flow conditions [21]. This analysis assumes the film to be an incompressible Newtonian fluid in laminar motion. The fluid interface is assumed to be smooth for the development of the fluid equations. However, the interface is assumed to be wavy when considering the gas. This allows the introduction of larger pressure gradients and interfacial shear forces. The fluid motion is then solved for one dimensional flow for three limiting cases. The first of these is the free falling film with no interfacial shear. The solution is the well known Nusselt profile with a zero velocity gradient at the interface. The second reference case is a falling film with zero velocity at the interface. This represents the limiting condition for complete downflow, since any increase in interfacial shear and hence interfacial velocity will result in upflow in part of the

film. The third reference case is a rising film with a zero velocity gradient at the wall. This represents a limiting condition for complete upflow, since any decrease in interfacial shear and hence interfacial velocity will result in downflow in part of the film. The film thickness at each reference case can be related to that at the other two cases. Also the interfacial shear for the second and third cases can be related but the exact value of interfacial shear is unknown except in the first case where it is zero. Therefore, the interfacial shear for any flow condition is defined in terms of a shear parameter, F , which is the ratio of the interfacial shear to that of the second case with zero interfacial velocity.

Rather than using a correlation for interfacial shear, Dukler and Maron define the shear in terms of the interfacial shear for the case of zero interfacial velocity.

$$F = \tau_i / \tau_0 = \frac{2 \tau_i}{\rho_L g \delta_0} \quad (41)$$

τ_0 = interfacial shear for case with zero liquid velocity at interface

δ_0 = film thickness with zero velocity at interface

By relating the film thickness to that for the freely falling film, Dukler and Maron solved the one dimensional flow equations for three cases: downflow, split flow, and upflow. The solutions of these respective cases are given below.

$$R_N^3 - 0.75 \sqrt[3]{4} R_N^2 F - 1 = 0 \quad (42)$$

$$R_N^3 - \frac{7F}{2} \sqrt[3]{0.5} R_N^2 + 4F^2 \sqrt[3]{0.25} R_N - \frac{2F^3 + 1}{3} = 0 \quad (43)$$

$$R_N^3 - 0.75 \sqrt[3]{4} F R_N^2 + 1 = 0 \quad (44)$$

where

$$R_N = \delta / \delta_N \quad (45)$$

Figure 3 shows that a single value of film thickness exists for values of $F < 1.0$. This corresponds to a state of total downflow. Two solutions of film thickness are possible for $1 < F < 1.59$. Thus the flow may be either downflow with circulation or split flow. For a value of $1.59 < F < 1.65$, three solutions are possible which correspond to upflow with circulation, split flow, and downflow with circulation. For $F > 1.65$, three solutions are

possible. These are upflow with circulation, total upflow, and downflow with circulation. Dukler and Maron use the existence of multiple solutions of film thickness to suggest that a variety of film states are likely at the flooding point and hence the states are by nature unstable. The large disturbance waves observed at the flooding point are explained as transitions between states. Dukler and Maron then speculate that a feedback from film thickness to capillary waves may exist. This would cause small changes in the interfacial shear and thus changes in the flow states. Such a feedback would be a type of limit cycle.

Figure 3. (From Reference 21)

SUMMARY

Since the early research in the 1930's, the approach to flooding has consisted of several stages. The early papers on flooding are somewhat sparse and confined mainly to chemical

engineering until the 1950's. In the late 1950's and early 1960's a large number of experimental studies were performed. The early work seemed to be directed toward empirical relations for packed columns. Analytical attempts to explain packed columns seemed to present an intractable problem and therefore a simpler geometry was sought which would yield to analysis. As a result, a number of studies were conducted in cylindrical tubes. By chance, all of the studies involved tubes in the diameter range from 25 mm (1 inch) to 50 mm (2 inches). A number of other parameters were studied such as water inlet configuration, gas inlet configuration, length to diameter ratio, and phase change effects.

The next major step in understanding the phenomenon of flooding came in the 1960's with the development of semi-empirical correlations which attempted to replace pure data fitting with somewhat of a physical basis. The Wallis correlation and the Kutateladze correlation are the most widely used semiempirical correlations. The correlations, however, are often misused by those attempting to apply them beyond their applicable ranges.

In the 1970's, a large amount of research in the form of large scale modeling was performed. Most of this work was done in support of reactor safety studies by either the nuclear industry or regulatory agencies. This work often was integral in that many effects in addition to flooding were studied in a combined experiment.

In the last few years, more detailed correlations such as those of Richter [44] have attempted to expand the original semi-empirical correlations and provide additional physical basis. Other work, especially by Dukler, has investigated the statistical nature of flooding and examined the structure of both large disturbance waves and small ripples. Dukler and Maron [21,39] have proposed a film model for flooding.

At this point, the authors would like to propose some suggestions for further research and speculate on possible approaches to flooding.

Dukler et al. [21] and Maron and Dukler [39] discuss the importance of the location of the liquid feed entrance relative to the top of the test section. Dukler's analysis assumes flooding to be a film phenomenon versus an entrainment phenomenon with "split flow" as one of the solutions for film thickness at the flooding point. The location of the liquid inlet must be different than the exit for internal recycle to take place in the film. By assuming that flooding is related but not identical to entrainment, it should be possible to reconcile the end effects due to a length of test section above the liquid feed. In this case, the entrained flow is responsible for the internal recycle. For a given

distribution of droplets at a given axial location, it should be possible to apply the results of research on droplet deposition to develop a distribution of droplets along the entire downstream section of the tube. The droplet distribution would be a function of gas velocity, droplet size, radial position (in polar geometries), and axial position. In addition, phase change effects may be added. The distribution of any internal recycle due to entrainment then becomes a convolution of a droplet deposition function and an entrainment source function such as given in references 30,33,34. The use of such an approach may require a relaxing of the criteria of no liquid out the top of the tube before flooding since droplet deposition implies only an asymptotic limit once a finite amount of liquid has been entrained.

Levy and Healzer [38] have proposed applying mixing length theory to a wavy, turbulent liquid-gas interface for cocurrent, annular flow. The analysis divides the flow into three regions: gas core, wall film, and wavy gas-liquid transition region. It may be useful to combine such an approach with Dukler's analysis [21,39]. In such an analysis, Dukler's analysis could provide the equations of liquid motion in the film. Work on droplet deposition, discussed above may aid in the analysis of the gas core. The transition region would present the remaining and perhaps most difficult element of the analysis. In this region, entrainment could be based on a model such as that of Ishii and Grolmes [31] modified for counter-current flow. Some statistical data on the shape of the film would then provide the final part of the solution.

In closing, the authors wish to state that, although flooding may never yield to a complete analytical solution, there are several areas of research which should reduce the uncertainty in the present level of knowledge such that accurate predictions may be made. The most useful areas of experimental research appear to be in the development of diagnostic techniques to determine the interface shape and liquid velocity profile within the film. Analytically, this is a good time for reflection to determine if solutions to other fluid problems might be applied to flooding.

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NOMENCLATURE

Symbols

A_h	area of holes in perforated plate, m^2
A_t	area of perforated plate, m^2
C, C_1, C_2	experimentally determined constants
C_i	interfacial friction factor
C_w	wall friction factor
C_p	specific heat capacity, J/kg.K
D	tube diameter, m (unless otherwise specified)
D_h	hole diameter (in perforated plate), m
D^*	Bond number
F	dimensionless shear factor
Fr	Froude number
g	acceleration of gravity, m/s^2
g_c	gravitational constant
Ga	Galiano number
h_{lg}	heat of vaporization, J/kg.K
H	dimensionless velocity defined by Richter
j	superficial velocity, m/s
J^*	dimensionless velocity defined by Wallis
K	dimensionless velocity defined by Kutateladze
C	experimentally determined constant
P	pressure, Pa
R	ratio of film thickness to Nusselt film thickness
Re	Reynolds number
Q_g	liquid mass flow rate divided by wetted perimeter, kg/m
S, S_g, S_g	flow areas defined by Imura, m^2
T	temperature, K
V	velocity, m/s
We	Weber number
α	void fraction
δ	film thickness, m
δ_N	Nusselt film thickness, m

ζ	factor involving experimental constant used by Imura
θ	angle of cut of tube entrance, degrees
μ	viscosity, Pa.s
ν	Kinematic viscosity, m ² /s
ρ	density, g/m ³
σ	surface tension, N/m
σ^1	modified surface tension used by Suzuki and Ueda, N/m
τ	shear, N/m ²

Subscripts

atmos	atmospheric
g	gas
h	hole (used for perforated plate correlations)
i	interface
in	inlet
l	liquid
LP	lower plenum
o	reference state used by Dukler (no interfacial velocity)
N	reference state for falling film with no gas velocity (Nusselt solution)
R	referenced to water
sat	saturation
w	wall

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