R-502 AND TWO NEAR-AZEOTROPIC ALTERNATIVES
PART II: Two-Phase Flow Patterns

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Flow patterns for horizontal intube flow boiling have been studied for the new refrigerants HP80 and HP62 and the conventional refrigerant R-502. The flow pattern observations were compared with several criteria utilized in horizontal flow boiling correlations for determining whether the entire circumference of a horizontal evaporator tube is all wet or only partially wet. Use of only the liquid Froude number Fr_L (utilized by numerous flow boiling correlations) is shown to be completely unreliable. Stratified (partially wet wall) flow was found to occur at Froude numbers up to 16 times those of the recommended threshhold values utilized by the correlations. A semi-empirical method for predicting stratification proposed by Klimenko and Fyodorov is an improvement but is only partially successful in predicting the present data.

KEY WORDS: Azeotrope, Boiling, Fluid Flow, Heat Transfer, Flow Patterns.

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INTRODUCTION

A two-phase flow and heat transfer test program was undertaken to obtain test data for two new replacements for R-502. The two new refrigerants are:

HP80 (60% R-125/2% R-290/38% R-22, by wt.) known as R-402A

and

HP62 (44% R-125/52% R-143a/4% R-134a, by wt.) known as R-404A

Two-phase flow patterns for forced flow evaporation inside 0.472 in. (12.00 mm) bore, horizontal tubes were investigated experimentally for the refrigerants HP80, HP62 and R-502. The tests covered mass velocities normally encountered in practice and a wide range of vapor qualities.

For horizontal intube boiling, characteristic of direct-expansion type evaporators, it is important to be able to predict the threshold between all wet and partially wetted tube circumferences locally along the internal bore of an evaporator tube. For horizontal flows the stratification of liquid to the lower portion and vapor to the top part of the tube has an adverse affect on the local heat transfer coefficient. Thus development of accurate criteria that predict the onset of stratification is an important step towards improving upon existing empirically-based flow boiling correlations. Thus, the main objective here is to report such flow pattern data and compare them to existing threshold prediction criteria.

Intube boiling tests were done concurrently with the flow visualization tests and are described in Part I, see Kattan, Thome and Favrat (1994). Flow patterns and boiling phenomena observed for evaporation of R-11 and R-123 inside horizontal annuli have been reported earlier in Kattan, Thome and Favrat (1992).

EXPERIMENTAL TEST FACILITIES AND PROCEDURES

The test facility, procedures and test fluids have been described in detail in Part I of this paper, see Kattan, Thome and Favrat (1994). Tests were run at saturation temperatures of 29.7°F, 36.3°F and 50.4°F (-1.3°C, 2.4°C and 10.2°C). Table 1 shows a summary of the experimental test conditions and Table 2 depicts the thermodynamic and transport properties of the three refrigerants at 36.3°F (2.4°C).

FLOW VISUALIZATION FACILITIES AND PROCEDURES

Sight glasses at both ends of the two horizontal test sections are utilized to monitor the flow patterns using both direct observations made during the tests and also viewing of the video tape recordings made of the flows. These tubular sight glasses are 4 inches (100 mm) long with an internal diameter of 0.472 in. (12.00 mm), the same as the internal diameter of the heated copper tubes in the test sections. They are installed inline with these copper tubes with very little disruption of the flow between the ends of the heated test sections and the sight glasses. The flow visualization studies are thus for adiabatic conditions, i.e. the sight glasses are not heated or cooled.

Two high speed video tape cameras capable of running at up to 10,000 images/sec are used to record the flow patterns. Speeds from 2000 to 4000 images/second are used experimentally depending on the flow regime. The images can be seen directly either on a television screen or on a PC monitor using a digitizer card. Individual frames can be saved on the computer hard disk (about 1 Mbytes per image). A color printer is used to print the images. The flow sequences at each test condition are saved on VHS tape. The tapes are then viewed to identify the specific type of flow pattern for the test conditions as a function of mass velocity, vapor quality, and saturation temperature and pressure for the particular refrigerant.

TWO-PHASE FLOW PATTERNS

Figure 1 taken from Collier and Thome (1994) depicts the two-phase flow patterns that may be observed along a horizontal evaporator tube. Depending on the flow conditions, not all of these patterns may occur or be seen at one time. Flow patterns can be classified according to the following definitions:

<u>Stratified flow</u>: Liquid and vapor phases flow separately with the liquid below and the vapor above a relatively smooth horizontal interface.

<u>Stratified wavy flow</u>: Liquid and vapor phases flow separately one below the other, respectively, with waves disrupting the interface (the waves however do not reach the top of the tube). Entrainment of droplets in the vapor phase can occur.

<u>Intermittent flow</u>: The fluid flows as liquid slugs separated by vapor zones containing a stratified wavy liquid layer flowing in the bottom of the tube. Entrained vapor bubbles are in the slugs concentrated near the top of the tube. The upper part of the tube remains wet from the residual liquid film left behind by passage of a slug.

<u>Annular flow</u>: Liquid and vapor phases flow separately with the liquid on the tube wall and the vapor in the central core. The liquid film is much thicker at the bottom of the tube than at the top. The upper part or even the majority of the tube wall may be dry as depicted at the right end of Figure 1. (For a thin, very chaotic liquid film covering only the bottom fraction of the tube, it can be difficult to differentiate between annular flow with partial dryout and stratified wavy flow). Entrainment of liquid droplets can occur at the very disrupted interface.

<u>Mist flow</u>: The vapor phase is the only continuous phase and liquid is present in the form of droplets (these atomized droplets are sometimes too small to be seen).

As mentioned earlier, for intube evaporation it is important to know whether or not the entire tube wall is continuously wetted with liquid at local conditions along the tube. For locations where there are dry areas on the tube wall, the heat transfer process between the vapor and tube wall is only single-phase forced convection with coefficients significantly below those for nucleate boiling, convective boiling or thin liquid film evaporation. The flows were therefore viewed to classify the two-phase flow depending on whether the cirumference of the inner tube wall was (i) always all wet, (ii) only partially wet all or some of the time or (iii) always all dry. It was not possible to be completely sure in all cases.

Figure 2 depicts a digitalized image of the stratified wavy flow pattern for HP80 taken from the video tapes. The mass velocity is 74985 lb/h ft^2 (102 kg/m^2 s), the vapor quality is 21%, the bubble point temperature is 36.3°F (2.4°C) and the pressure is 102.2 psia (7.05 bar). The circumference of the sight glass tube is only partially wet.

The present flow pattern observations were all taken at the two sight glasses located at the exits of the two heated test sections. None are for the inlet sight glasses.

STRATIFICATION CRITERIA USED IN FLOW BOILING CORRELATIONS

Shah Criterion:

Shah (1982), Gungor and Winterton (1986, 1987) and Kandlikar (1990) have used a very simple criterion to determine if the wall of a horizontal evaporator tube is all wet or not. According to Shah the tube wall is only partially wetted around its circumference if

$$Fr_L = G^2/[\rho_L^2 \; g \; D_i] < 0.04 \qquad (1)$$

where Fr_L is the liquid Froude number, G is the total mass velocity, g is the acceleration due to gravity and D_i is the internal tube diameter. This effect is important because the heat transfer coefficient is lower than that for a vertical tube for identical local conditions if the tube wall is partially dry.

Kandlikar evaluated his boiling databank for different values of Fr_L and retained Shah's value of 0.04. Gungor and Winterton did the same and arrived at the criterion $Fr_L < 0.05$ for the stratification threshold. Thus, this criterion and its values were derived from statistical analysis of boiling heat transfer databanks to improve correlation accuracy rather than from actual physical observations of the flows.

Figures 3 and 4 depict the flow data for HP80 over a wide range of vapor quality and mass velocity. The observations are classified as being All Wet, Partially Wet, All Dry or Partially Wet? (for uncertain cases). As can be seen, all of the partially wetted wall data are above both the 0.04 and 0.05 threshold lines. In fact, partially wetted tube walls persist up to liquid Froude numbers of 0.56. At vapor qualities ranging from 65-80%, the flow surpasses the complete dryout point, under which conditions a very fine mist flow occurs with all the droplets sometimes completely invisible. Checking against the heat transfer data for these same mist flow regime data, they were seen to be considerably below the values before dryout occurred.

Figures 5 and 6 depict the tube wetting data for HP62. All of the partially wetted data in these figures are above both the 0.04 and 0.05 threshold lines. In fact, partially wetted tube walls persist up to liquid Froude numbers of 0.65, i.e. up to 16 and 13 times the threshold values of 0.04 and 0.05, respectively. Dryout is seen to have been surpassed for two test conditions at vapor qualities of 89% and 97%.

Figure 7 presents the flow data for R-502 over a wide range of vapor quality and mass velocity. Several partially wetted wall data are below the value of 0.05 but all of the partially wetted wall data are above the 0.04 threshold line. In fact, partially wetted tube walls persist up to liquid Froude numbers of 0.47. Complete dryout, i.e. all dry walls with mist flow, was only observed at vapor qualities approaching 100%, in contrast to the HP80 data.

The test observations conclusively show that the partially wetted wall condition persists up to liquid Froude numbers substantially higher than 0.04 or 0.05, by more than an order of magnitude in some cases. One of the most apparent weaknesses of using only Fr_L as the threshold criterion is that it thus must apply from the inlet to the outlet of an evaporator tube, which is totally unreasonable based the change of flow patterns with vapor quality along an evaporator tube as shown in Figure 1. Therefore the liquid Froude number alone is <u>not</u> satisfactory for establishing whether or not the tube wall is all wet or partially wet. Hence the use of this criterion in flow boiling correlations to predict the threshold of stratified flow and as a parameter to correlate the reduction this causes in the heat transfer coefficient is not appropriate.

<u>Klimenko-Fyodorov Criterion</u>:

Klimenko and Fyodorov (1990) have developed a mechanistic criterion for determining the transition from stratified to unstratified flow. Unstratified flow was defined as all flow regimes with <u>continuous</u> wetting of the whole tube circumference (which includes intermittent or slug flows). Completely stratified flow and wavy flow (since part of the tube wall is not wetted) and annular flows with dryout over the top portion of the tube were classified as stratified flow. According to their model, transition from stratified wavy flow to annular flow is due to entrainment-deposition of liquid droplets on the tube wall while transition from stratified flow to intermittent flow depends on the development of gravitational waves on the liquid-vapor interface.

Using a two-phase flow databank composed of both visual data and some nonvisual data (type of flow regime based on an intuitive analysis of boiling data with circumferential temperature measurements around the tube wall), Klimenko and Fyodorov determined the constants and exponents for their following semi-empirical expression:

$$F = 0.074\ Fr_L\ (D_i/b)^{0.67}\ Fr_V + 8\ [1 - (\rho_V/\rho_L)^{0.1}]^2\ Fr_L \qquad (2)$$

where for: $F > 1.0$ Unstratified flow exists

$F < 1.0$ Stratified flow exists

They defined the liquid Froude number using the superficial liquid velocity (u_L) such that

$$Fr_L = \rho_L\ u_L^2\ /[(\rho_L - \rho_V)\ g\ D_i] \qquad (3)$$

and the vapor Froude number using the superficial vapor velocity (u_V):

$$Fr_V = \rho_V\ u_V^2\ /[(\rho_L - \rho_V)\ g\ D_i] \qquad (4)$$

The tube internal diameter is D_i, g is the acceleration due to gravity and b is the Laplace constant given as:

$$b = \{\ \sigma_L/[g\ (\rho_L - \rho_V)]\}^{1/2} \qquad (5)$$

The liquid and vapor superficial velocities are determined from the following expressions where x is the vapor quality and G is the total mass flux:

$$u_L = G\ (1-x)/\rho_L \tag{6}$$

$$u_V = G\ x/\rho_V \tag{7}$$

The flow pattern observations for HP80, HP62 and R-502 are compared to the Klimenko and Fyodorov criterion in Figures 8 to 12. The above criterion was transformed into modified liquid and vapor Froude numbers as was done by Klimenko and Fyodorov in their paper such that the threshold becomes a curve. The modified liquid Froude number is given by

$$(Fr_L)_{mod} = Fr_L^{0.5}\ [1 - (\rho_V/\rho_L)^{0.1}] \tag{8}$$

and the modified vapor Froude number by

$$(Fr_V)_{mod} = Fr_V^{0.5}\ (D_i/b)^{0.33} \tag{9}$$

Figures 8 and 9 depict the HP80 data plotted as modified Froude numbers. All of the Partially Wet data are situated inside the correct region. Instead the majority of the All Wet data fall in the Partially Wet region while the All Dry data (not classified by this method) lie in the All Wet region. Thus the Klimenko-Fyodorov criterion is only partially successful in delineating the data.

Figures 10 and 11 show the HP62 data. Here most of the Partially Wet data are situated inside of the correct region with a minority just over the boundary in the All Wet region. Instead about half the All Wet data fall in the correct region and the rest in the Partially Wet region. The few All Dry data lie again in the All Wet region. Thus poor segregation of the data by the Klimenko-Fyodorov criterion is again evident.

Figure 12 depicts the R-502 data. Here neither the Partially

Wet nor the All Wet data are separated into their respective regions by the method. Two All Dry data points also lie in the Partially Wet region while one is in the All Wet region.

Review of the types of flow patterns for the All Wet data incorrectly lying in the Partially Wet region showed that most of these were in the intermittent flow regime. The wetting of the top of the tube was seen to be in the form of a thin liquid film left behind by passage of the large scale liquid slugs or waves. This is the slug flow regime shown in Figure 1 (this flow pattern is defined as intermittent flow in our terminology, see the definition given earlier).

Another aspect influencing the threshold between Partially Wet and All Wet wall conditions is the dryout phenomenon in annular flow. In vertical flow dryout of the annular film occurs essentially all around the circumference of the tube at the same location along the tube. Instead the dryout boundary in horizontal flow does not occur at a fixed location since the film is thinner at the top of the tube and dryouts out there first. Annular flow then proceeds with the annular film wetting only a portion of the tube wall as illustrated in Figure 1. Thus the dryout boundary is a function of both the angle around the circumference of the tube and the position along the tube. Consequently a Partially Wet wall can persist up to a higher vapor quality in horizontal flow than for vertical flow under the same conditions.

The Klimenko-Fyodorov criterion is an improvement upon the Shah method. The All Wet and the Partially Wet region boundaries represent a transition from one type of flow pattern to others and hence is probably better represented by a zone rather than a curve. One drawback of this method is that it does not include the transition to the mist flow regime, which is important for the accurate prediction of heat transfer coefficients at high vapor qualities in refrigeration system evaporator tubes.

The analysis of the Wet and Partially Wet wall flow data and the two-phase flow patterns is continuing. Ways to improve the Klimenko-Fyodorov criterion or add supplimentary criteria are under investigation.

CONCLUSIONS

Flow pattern data for intube flow boiling were taken for refrigerants HP80, HP62 and R-502 and compared with several criteria utilized to determine whether the entire circumference of a horizontal evaporator tube is wet or only partially wet. The Shah approach using only the liquid Froude number Fr_L was shown to be too simplistic and unreliable. Many flows are in the stratified regime even though their liquid Froude numbers were 13 and 16 times above the recommended threshold values of 0.04 and 0.05, respectively. The new Klimenko-Fyodorov method appears to be an improvement but still does not predict the present data satisfactorily.

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NOTATION

b	Laplace constant
D_i	Internal tube diameter (m)
F	Factor in Eq. (2)
Fr_L	Liquid Froude number
$(Fr_L)_{mod}$	Modified liquid Froude number
Fr_V	Vapor Froude number
$(Fr_V)_{mod}$	Modified vapor Froude number
G	Total mass velocity (kg/m^2 s)
g	Gravitational acceleration (9.81 m/s^2)
u_L	Superficial liquid velocity (m/s)
u_V	Superficial vapor velocity (m/s)
x	Vapor quality
ρ_L	Liquid density (kg/m^3)
ρ_V	Vapor density (kg/m^3)
σ_L	Surface tension (N/m)

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Table 1. Test conditions for two-phase flows.

Fluid	T_{sat} °F (°C)	P_{sat} psia (bar)	Mass Velocity 1000 x lb/h ft^2 (kg/m^2 s)	Heat Flux Btu/h ft^2 (W/m^2)	Vapor Quality (%)	Data Points
HP80:	29.7 (-1.3)	91.4 (6.30)	233 (317)	1428-6606 (4503-20,836)	1.7-54.7	24
	36.3 (2.4)	102.2 (7.05)	75, 147, 234 (102, 200, 318)	1391-7260 (4387-22,897)	1.7-90.0	96
	50.4 (10.2)	128.7 (8.88)	223 (303)	1455-9067 (4588-28,597)	2.8-83.6	34
HP62:	29.7 (-1.3)	85.4 (5.89)	235 (320)	1688-6905 (5323-21,777)	1.9-54.7	24
	36.3 (2.4)	95.8 (6.61)	75, 147, 234 (102, 200, 318)	1084-9686 (3418-30,551)	1.7-92.1	98
	50.4 (10.2)	121.2 (8.36)	221 (300)	1386-9693 (4372-30,573)	1.6-89.3	34
R-502:	36.5 (2.5)	89.9 (6.20)	73.5, 147, 221 (100, 200, 300)	1350-8789 (4257-27,720)	1.8-98.6	84

Table 2. Physical properties at 36.3°F (2.4°C).

Property	HP80	HP62	R-502
Saturation Pressure psia (bar)	102.2 (7.05)	95.8 (6.61)	89.4 (616.8)
Liquid Density lb/ft^3 (kg/m^3)	78.5 (1257)	72.7 (1164)	82.0 (1313)
Vapor Density lb/ft^3 (kg/m^3)	2.32 (37.2)	2.05 (32.9)	2.18 (34.9)
Liquid viscosity cp (mN s/m^2)	0.205 (0.205)	0.181 (0.181)	0.226 (0.226)
Vapor Viscosity cp (mN s/m^2)	0.0122 (0.0122)	0.0117 (0.0117)	0.0121 (0.0121)
Liquid Specific Heat Btu/lb°F (kJ/kg K)	0.289 (1.211)	0.321 (1.346)	0.283 (1.184)
Vapor Specific Heat Btu/lb°F (kJ/kg K)	0.195 (0.817)	0.224 (0.939)	0.169 (0.708)
Liquid Thermal Cond. Btu/h ft °F (W/m K)	0.037 (0.064)	0.044 (0.076)	0.042 (0.073)
Latent Heat Btu/lb (kJ/kg)	68.7 (159.4)	71.7 (166.3)	62.4 (144.9)
Surface Tension (dyne/cm)	8.75	7.46	9.92
Critical Pressure psia (bar)	599.6 (41.35)	538.7 (37.32)	590.9 (40.75)
Molecular Weight	101.55	97.60	111.63
Dew Point Temperature °F (°C)	38.1 (3.4)	37.1 (2.8)	36.3 (2.4)
Bubble Point Temperature °F (°C)	36.3 (2.4)	36.3 (2.4)	36.3 (2.4)

LIST OF FIGURES

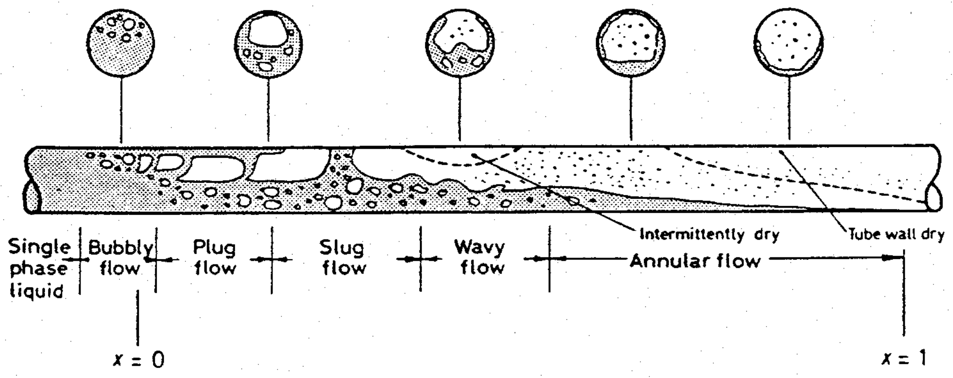

Figure 1. Flow patterns inside a horizontal evaporator tube.

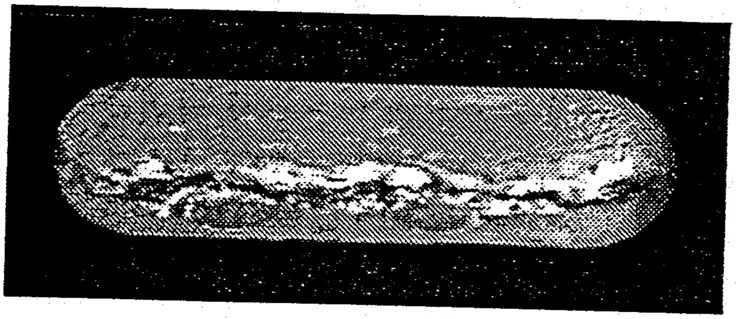

Figure 2. Stratified wavy flow pattern for HP80.

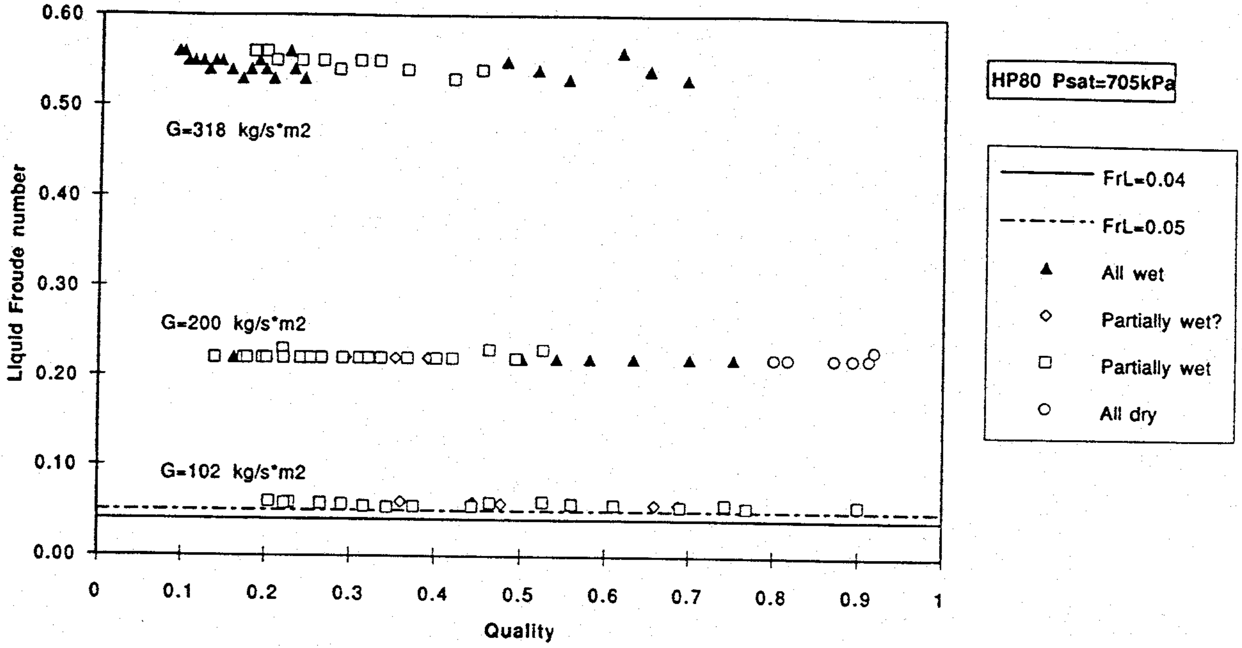

Figure 3. HP80 compared to Shah criterion at 36.3°F (2.4°C).

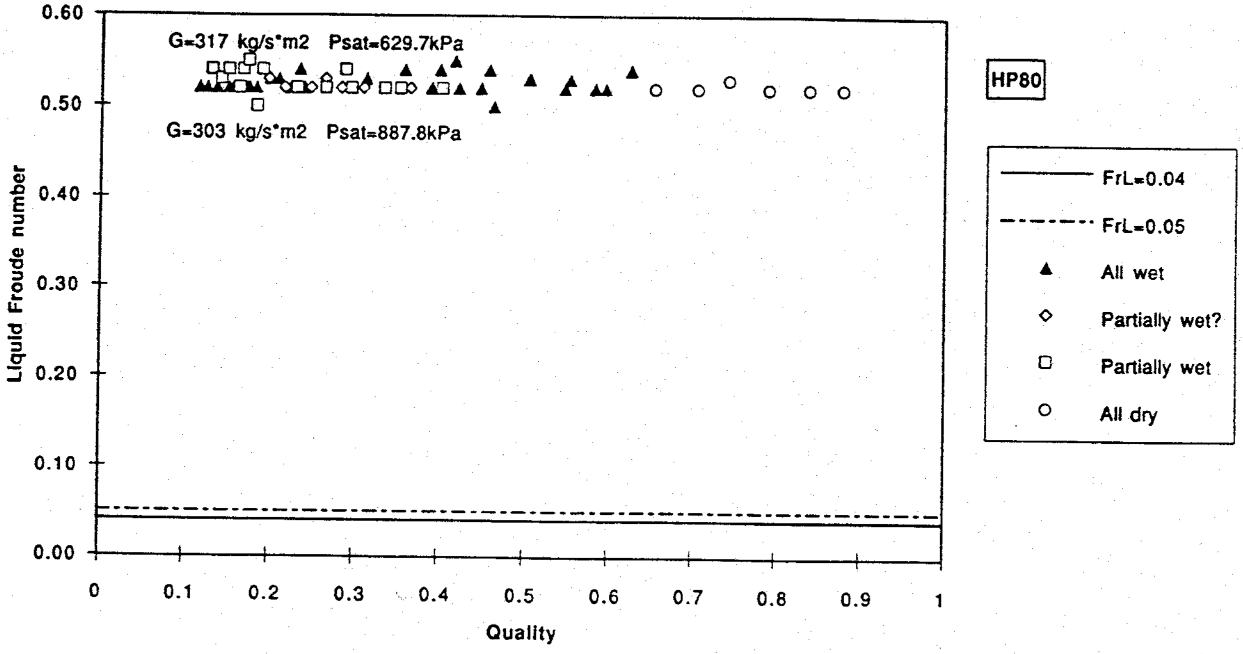

Figure 4. HP80 compared to Shah criterion at two pressures.

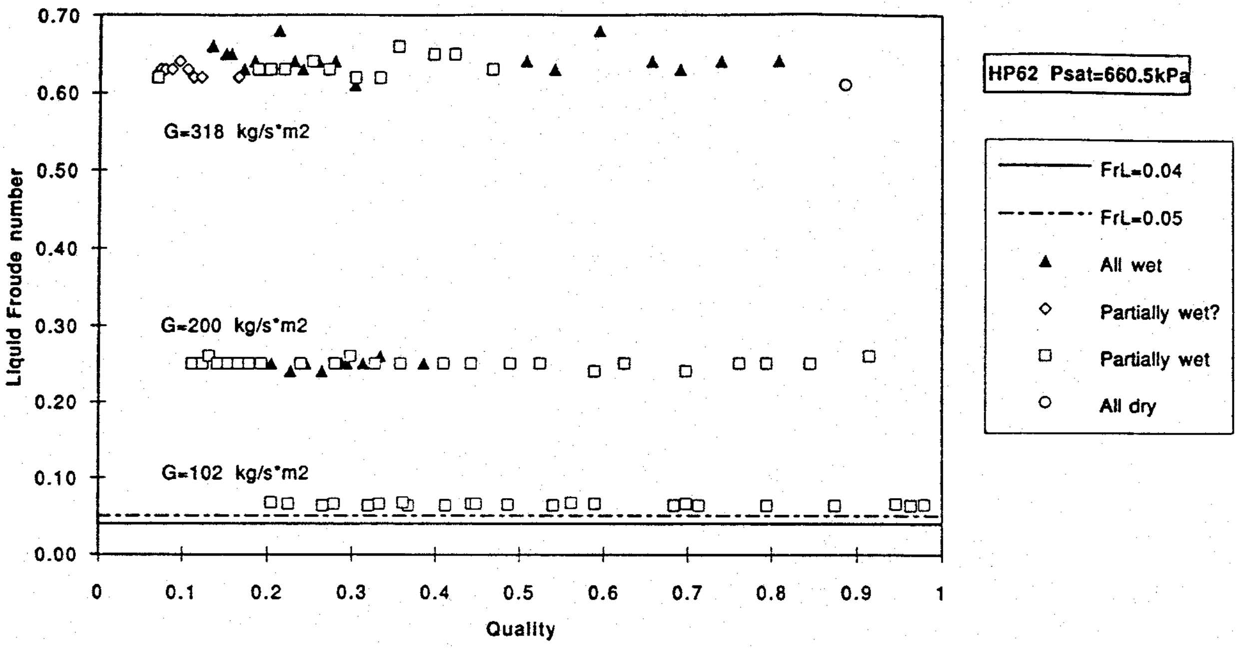

Figure 5. HP62 compared to Shah criterion at 36.3°F (2.4°C).

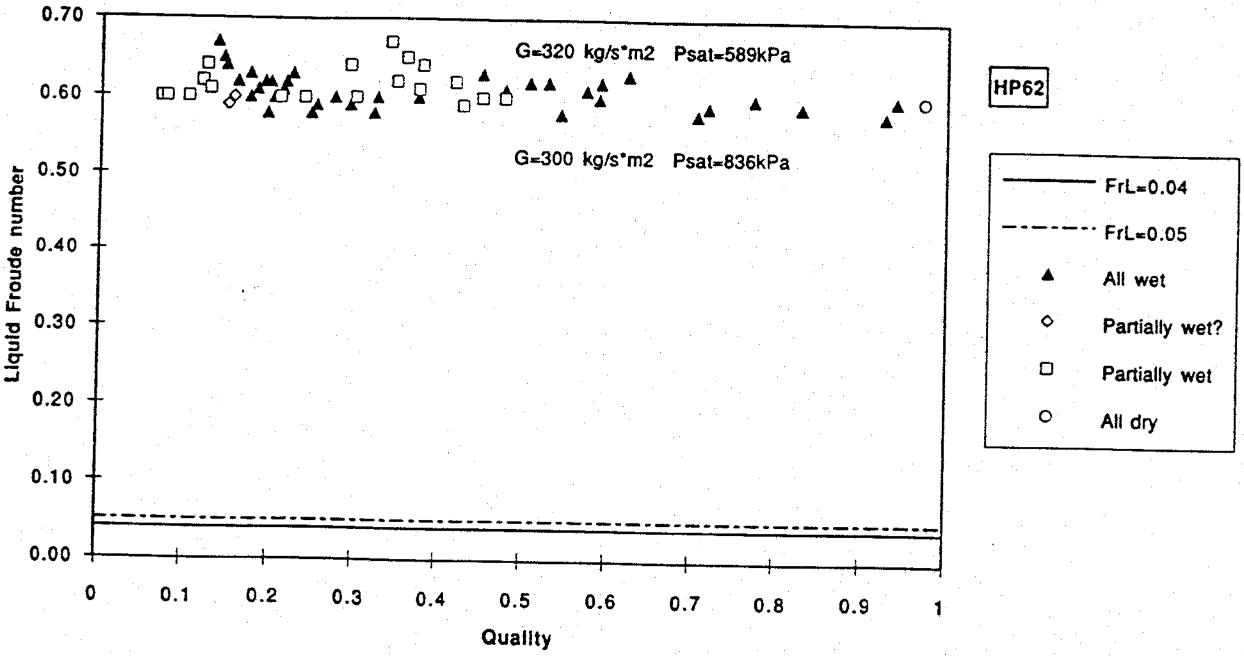

Figure 6. HP62 compared to Shah criterion at two pressures.

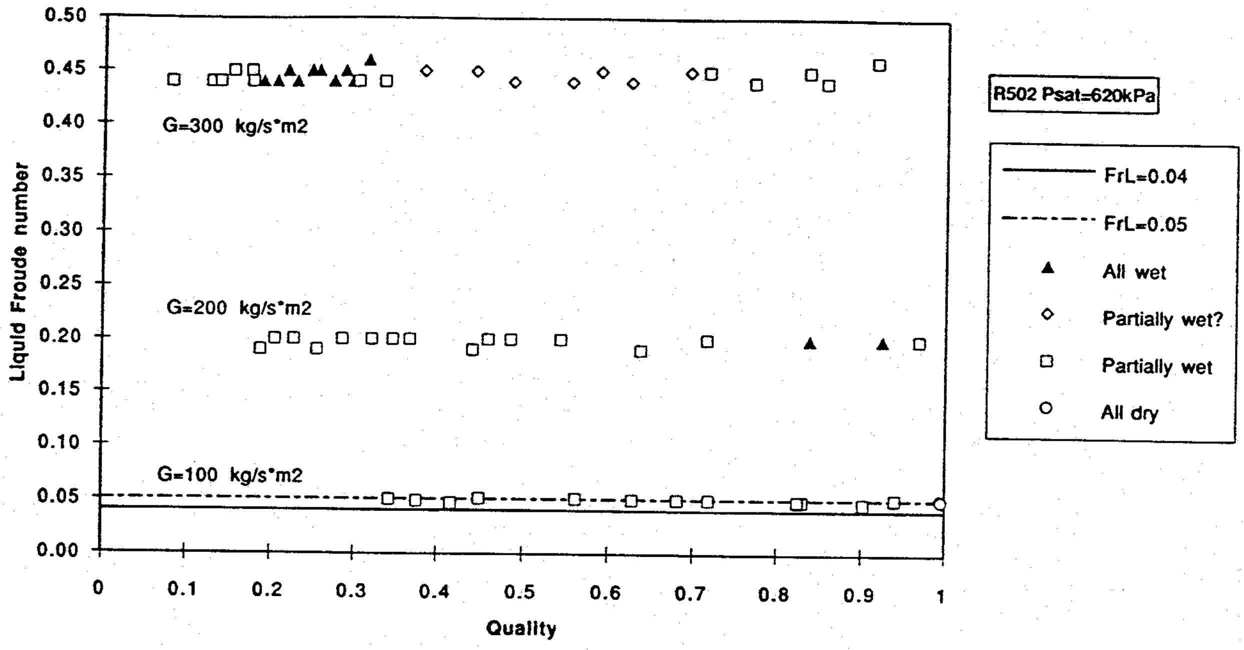

Figure 7. R-502 compared to Shah criterion at 36.5°F (2.5°C).

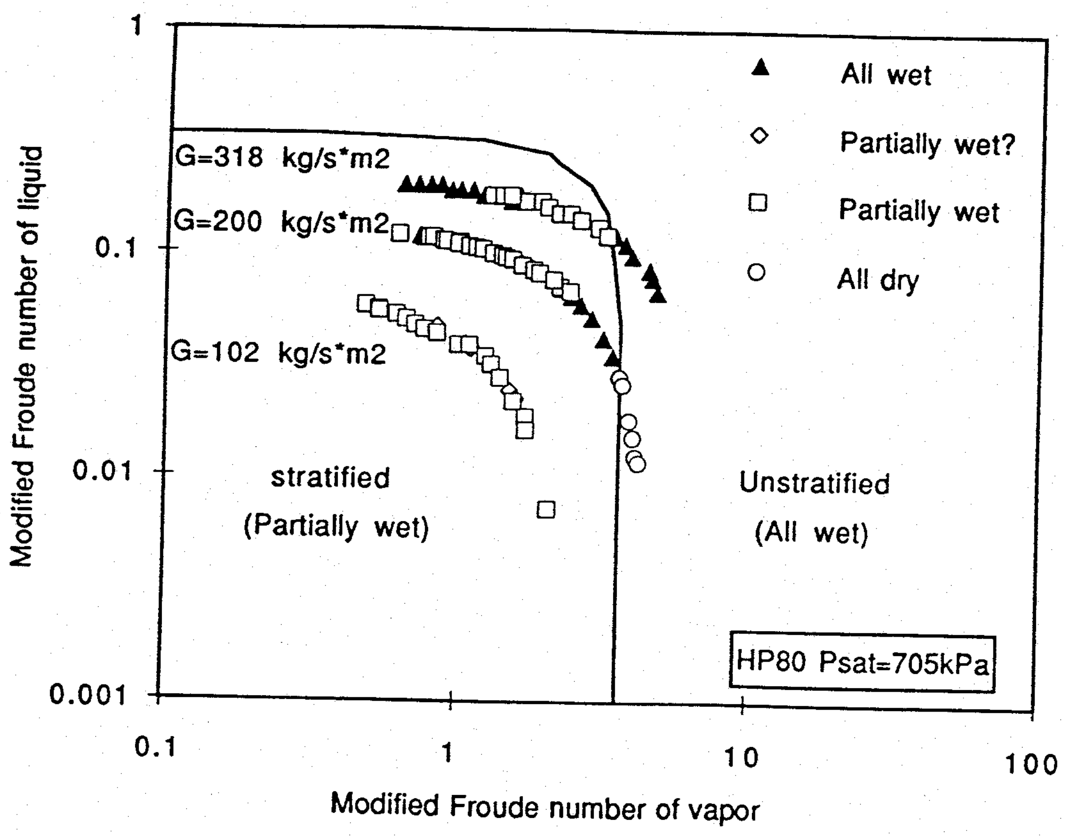

Figure 8. HP80 compared to Klimenko-Fyodorov criterion.

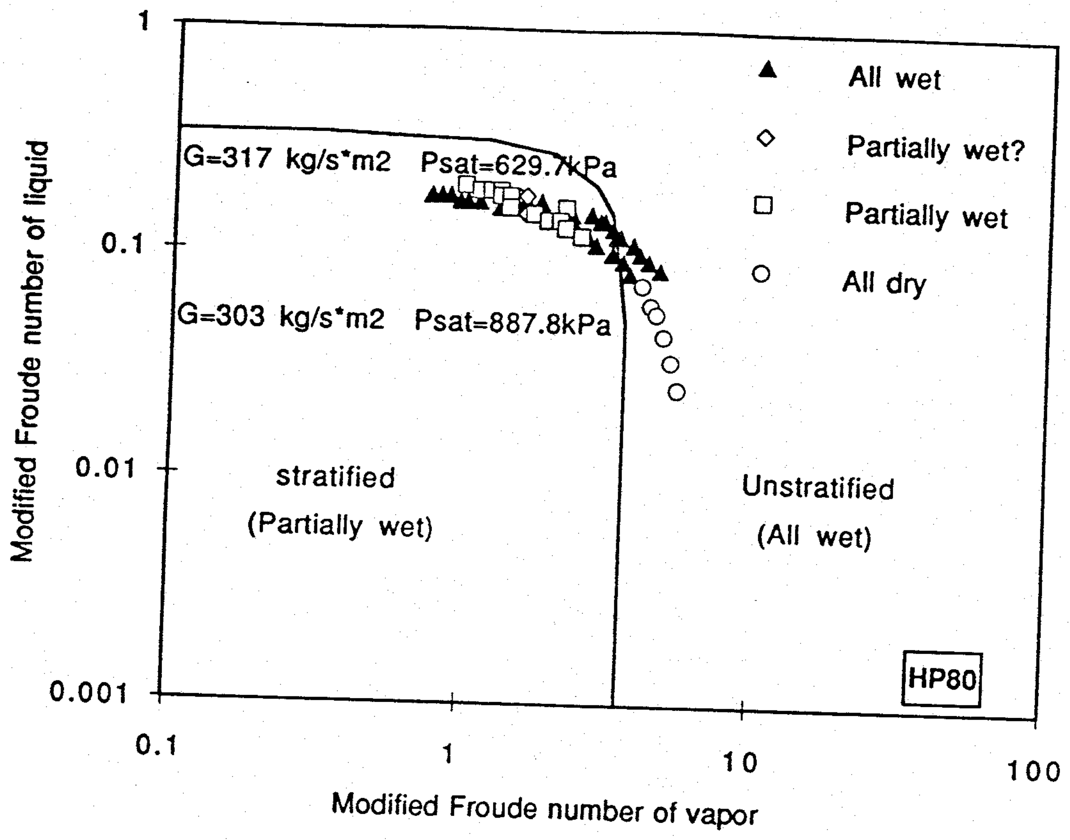

Figure 9. HP80 compared to Klimenko-Fyodorov criterion.

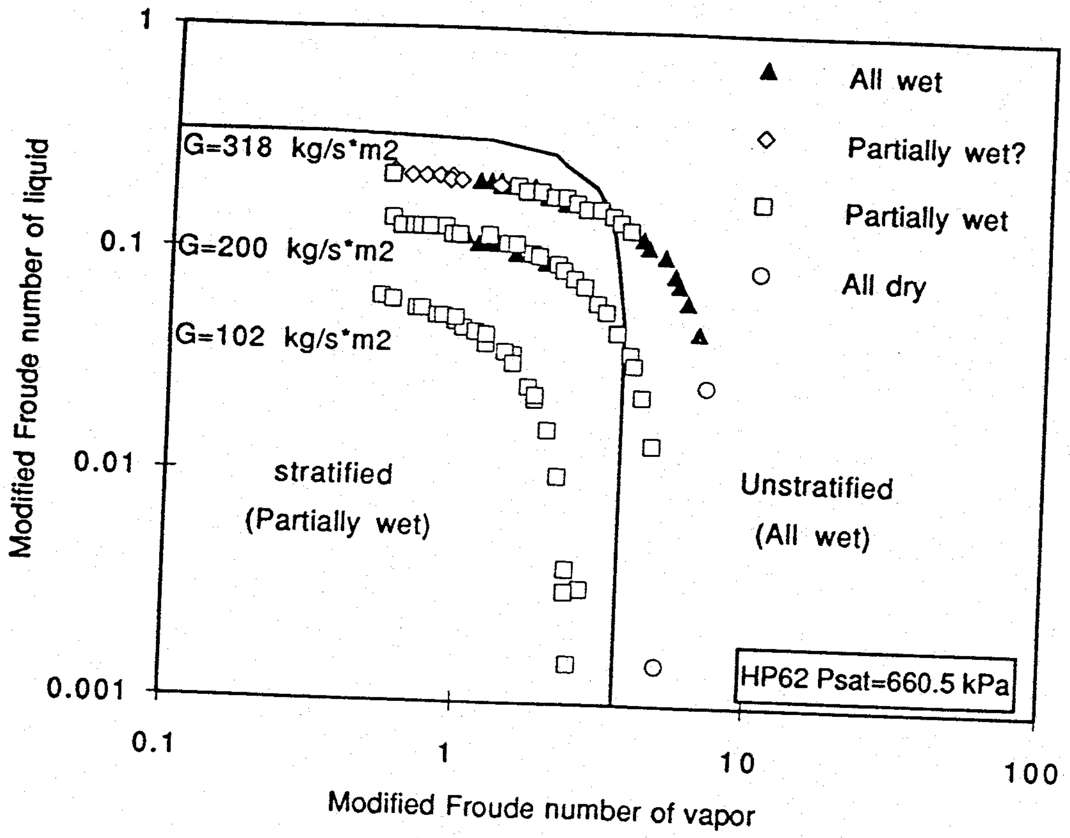

Figure 10. HP62 compared to Klimenko-Fyodorov criterion.

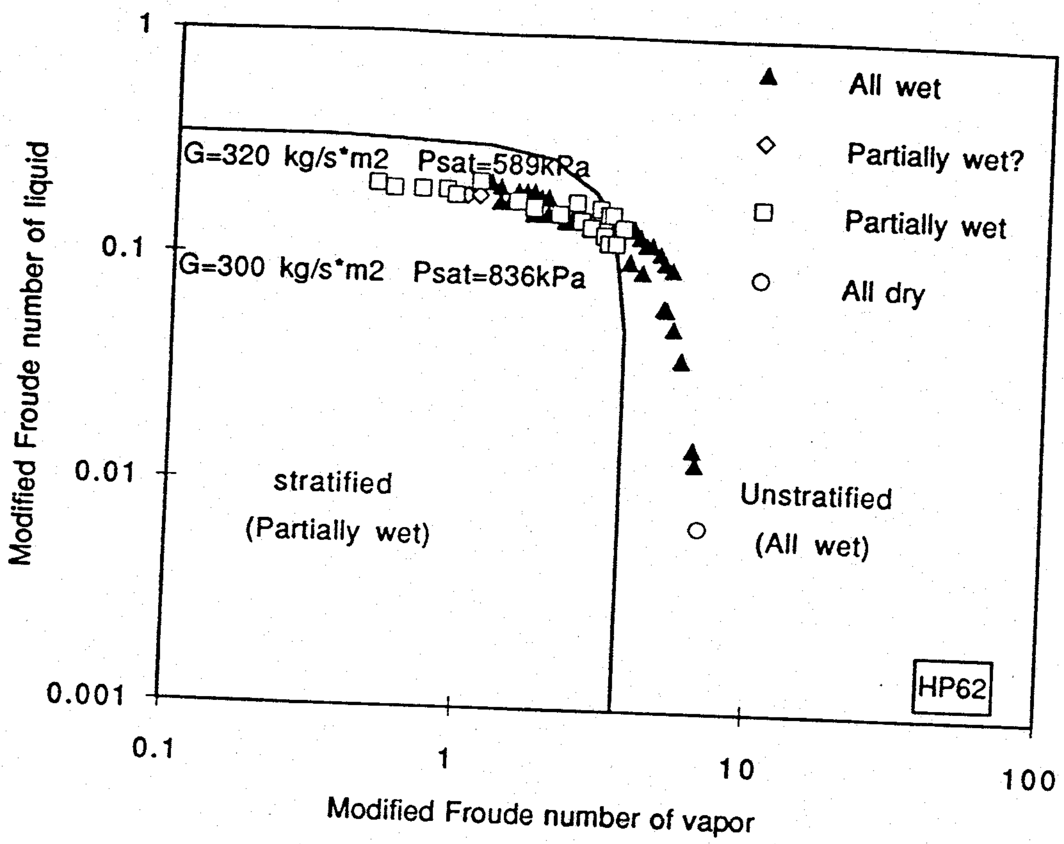

Figure 11. HP62 compared to Klimenko-Fyodorov criterion.

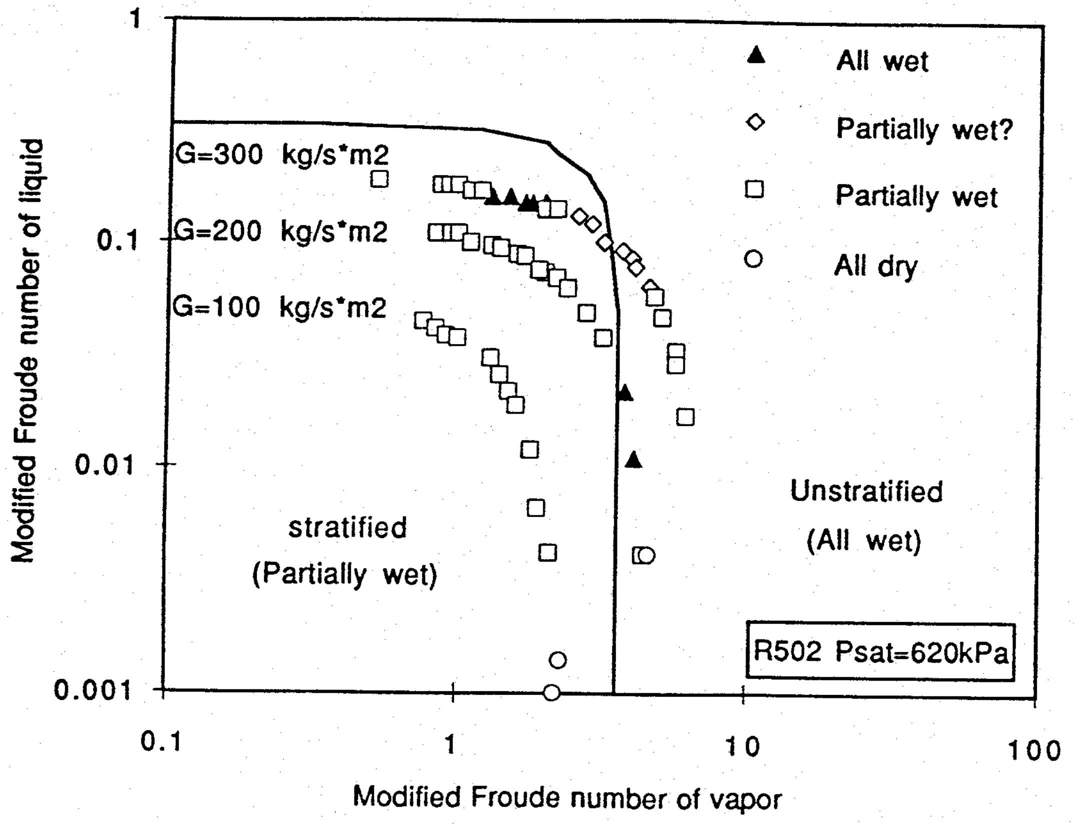

Figure 12. R-502 compared to Klimenko-Fyodorov criterion.