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CARRYING CAPACITY OF MILKLINES

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ABSTRACT: This paper reports results of a theoretical and laboratory study of two phase flow characteristics in dual purpose milklines. The experimental setup and conditions are described. Comparisons with previous experimental and theoretical predictions are made. Recommendations for revision of US and International standards are presented.

KEYWORDS: Milklines, Two Phase Flow

CARRYING CAPACITY OF MILKLINES

I. Introduction

It is clear from both research and field experience that increasing the slope of milklines increases their carrying capacity and that looped milklines are preferable. The present US standard (1) does not make allowances for slope. The present ISO standard (2) incorporates a correction for length but not slope. A 1982 Cornell research publication (3) recommended corrections for slope but not length. Both international and US guidelines for the effective carrying capacity of milklines are being revised at present.

In both the US and Europe, it is widely (although not unanimously) accepted that stratified flow, rather than slug flow, is the preferred flow condition in dual-purpose milklines (those which carry both milk and air admitted through the claw during milking). Currently the appendix to 3-A accepted practice 606 is used for specifying milkline carrying capacity in the US. These recommendations originated from a 1978 Californian guideline (4) which limited the number of milking units to the square of the pipe diameter, in inches, i.e. a 2" line could have a maximum of 4 units per slope. While the scientific basis for this recommendation was never published, it did ensure that stratified milk flow is likely to be the normal flow condition in typical milking parlor installations.

Both the ISO and British (5) guidelines for the carrying capacity of milklines are based on a maximum acceptable vacuum drop due to friction of 3 kPa (0.9" Hg). This criterion does not take into account whether slug flow occurs due to the combined effects of high fill depth and high air velocity. If slugging does occur this method of calculation is flawed.

If stratified flow is accepted as the preferred condition for milk flow in the milkline, then the ISO and British standards may be inadequate for some large diameter milklines in milking parlors. Conversely, US 3A standards may be inadequate for some small diameter stanchion barn pipelines with little slope. The existing ISO and British guidelines are actually higher than US standards for dead-ended milklines that are more than about 200 ft (60m) long or for looped milklines 500 ft (150 m) or more in total length. This is because both the ISO and British standards take the total length of the milkline into account.

Initial measurements by Spencer (6), on one farm only, indicate that up to 16 units per slope might be acceptable on a short, looped 3" milkline. More extensive laboratory studies, calculations and field measurements were needed before the present ISO, 3-A or the new ASAE guidelines could be changed. This paper reports results of a theoretical and laboratory study of two phase flow characteristics in dual purpose milklines.

II. Theoretical Study

A theoretical model was developed to determine milk carrying capacity, air and milk velocities and pressure drop as a function of pipe diameter, fill depth and slope and air admission rate. Gates et al (3) used Manning's equation, commonly used for open channel flow, to predict water flow rates in a pipeline as a function of fill depth and slope. The method used by Gates et al (3) was modified to account for density and viscosity differences between milk and water.

The model was further extended to determine frictional pressure drop during stratified flow as a function of pipe length and air velocity.

The use of Manning's type equations assume that milk and air flow are stratified and that there is no momentum transfer between the air and milk (i.e. the air flow in the top of the pipe has no effect on the milk flow in the bottom of the pipe). If slugging of milk occurs this prediction method is no longer valid. Slugging is caused by momentum transfer between the air and milk. Thus, near the transition zone between stratified and slug flow the assumption of negligible momentum transfer is violated.

Flow pattern maps are commonly used to predict the transition between various flow regimes. Flow pattern maps, in general, are highly empirical. The use of empirical flow pattern maps outside the range of the test conditions is likely to produce uncertain results. There have been no maps developed for the conditions prevailing in milking machine pipelines (Transient air flow and pulsed milk flow mixed in inclined pipes under vacuum conditions).

As a preliminary estimate, the transition to slug flow was determined using predicted superficial air and milk velocities and the commonly accepted flow pattern map illustrated in Figure 1. This map was developed from flow data for air/water mixtures in horizontal pipes at atmospheric pressure. The region of interest for many milking conditions is in the critical transition zone between stratified, bubble, slug and wave flow on this map. Typical results using this analysis method are shown in Table I. These theoretical results indicate that:

1. Carrying capacity increases markedly with increasing slope of milk line (e.g. almost 40% greater at 1.5% slope compared with 0.8%).
2. Fill depth has a major effect on carrying capacity (e.g. capacity is more than doubled at 0.5 compared with 0.3).
3. Total length of the milk line is limited to 100 m or less (assuming no slugging and max pressure drop of 3 kPa) only when diameter is less than 60 mm, fill depth is greater than 0.5, and a milking unit falls or is kicked off by the cow.
4. The calculated velocities for air and milk fall in or near the transition zone between stratified and slug flow on existing flow pattern maps.

III. Experimental Study

Physical phenomena occurring in milking systems which are not accounted for in the above theoretical formulation include:

1. The effect of milk foaming on the free space available for air flow, interfacial shear stress and slug formation.
2. The momentum transfer between air and milk velocity under vacuum conditions and its effect on fill depth, wave formation and slugging.
3. The effect of flow disturbances caused by the pulsed entry of milk perpendicular to the milk flow direction in the pipeline.
4. The effect of slope on development of surface waves due to milk velocity.
5. The effect of milk viscosity and density versus water on the validity of Manning's equation.
6. The effect of combined steady and transient air flow and pulsed milk flow on

local fill depth, wave formation and slugging.

Laboratory measurements were done to investigate these effects and validate the theoretical model. The experimental conditions and measurement points were chosen to replicate a worst case scenario or the expected maximum fill depths and slugging conditions. The experimental layout is illustrated in Figure 2. Details of the experimental apparatus and procedures are given below:

Physical Layout

Slopes tested included 0.5, 1.0 and 2.0 percent.

Configurations included both looped and dead ended lines.

Line lengths of 29 m (94 ft) per slope and 12 m (42 ft) per slope were tested

Liquid Flow

Liquid flows were increased in increments of 4.5 L/m which is representative of the peak flow rate from one milking unit . Note that total liquid flow is expressed on a per slope basis. Thus a flow of 50 L/m indicates a liquid flow of 50 L/m in each of the two slopes of a looped line.

The fluid used for most of the trials was formulated to match the viscosity, density and foaming characteristics of fresh warm milk. Comparison trials were made with plain water at room temperature.

Liquid was introduced in pulses into commercial, pulsating milking claws and transported to test section "A" section via 16 mm (5/8 inch) diameter long milk tubes. Additional liquid was introduced at steady flow rates into upstream sections of the milkline.

Air Flow

Steady state air flow representative of normal unit consumption was introduced in the ratio of 10 L/m of air per 4.5 L/m of liquid (0.3 scfm of air per 10 lb/m of liquid). The normal air vents supplied this air through the milking units. The additional steady state air admission was introduced at the distal end of the milk line.

Transient air admissions ranging from 50 L/m to 500 L/m per slope (1.8 to 18 scfm per slope) were introduced through an airflow meter fitted with an automatically actuated air valve into a milk inlet 1 meter upstream of the last milk inlet. The transient air admission was introduced for a period of 6 s after allowing the steady state air admission and liquid admission to reach equilibrium conditions. Note that all air flowrates are expressed on a per slope basis, i.e. for looped lines with two slopes 120 L/m (4.2 scfm) steady air flow and 100 L/m (3.5 scfm) transient air flow indicates a total air admission of 240 L/m 8.5 scfm) at the distal end of the looped line and 200 L/m (7.1 scfm) of transient air admission at the center of the test section.

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Materials and Fittings

Straight PVC pipe sections were used for the bulk of the measurements. Internal diameters were within 0.1 mm (0.004) inches of standard stainless steel milklines.

Commercially available milking system fittings were used for elbows. Comparative runs were made with stainless steel pipe sections to confirm the adequacy of using PVC.

Fill Depth and Vacuum Measurements

Dynamic measurements of vacuum were made at the distal end of the milk line, at the claw and inlet of the milking unit closest to the receiver, and at the receiver.

Milkline fill depth was measured dynamically at a single point just upstream from an elbow, near the receiver, and 1 m (39 in) downstream of the last milk inlet.

Dynamic fill depth measurements provided information on the frequency, velocity and length of slugs. These were correlated with simultaneous measurements of vacuum fluctuation.

IV. Results and Discussion

Milkline Fill Depth and Vacuum Fluctuation: The data presented in Figure 3 represents typical conditions before slugging occurs. Several characteristics of milkline flow are apparent from this graph. During periods of stratified flow with steady air admission (0 to 4 s), there is a cyclic variation in fill depth due to the pulsed entry of milk form the long milk tube into the milkline. These pulses of milk produce waves which persist for several meters downstream of the inlet.There was a drop in vacuum of about 1 kPa caused by frictional losses due to the increased transient air flow.

The data presented in Figure 4 represents typical conditions when slugging was induced by the combined effects of steady and transient air admission (Transient air admission begins at 4 s). The transient vacuum drop associated with this condition is about 2 kPa (0.6" Hg). Note that the fill depth after the slug passes is reduced because milk is being removed from the line by the slug.

The major vacuum fluctuation occurring as a result of slugging usually occurred within 2 s of the beginning of transient air admission. The transition to slug flow is not distinct especially at low slopes and low transient air admission. As air flow is increased, the waves produced by pulsed milk entry begin to grow until they eventually fill the entire pipe cross section. The vacuum drop in the milkline during transient air admission is due to both frictional losses and slug formation and motion. The slug forms a wall of fluid which can support a vacuum difference. The vacuum difference across the slug acts to accelerate the slug and to oppose frictional forces between the milk and pipe wall.

For most cases in the region of interest for milking systems, a criterion of a 2 kPa (0.6" Hg) transient vacuum drop below the average vacuum in the milkline is a reasonable indicator of slug formation. In some cases near the transition zone, large waves may occur and appear by visual inspection to be slugs but do not fill the entire pipe and produce fluctuations less than 2 kPa (0.6" Hg). In lines with low slopes and at low levels of transient air admission and high liquid flow slow moving slugs may be formed which produce vacuum fluctuations less than 2 kPa (0.6" Hg).

Vacuum Fluctuations in the Milkline, Claw and Receiver. The vacuum fluctuation measured in the milkline just downstream from the last milk inlet is plotted against the vacuum fluctuations in the claw and at the distal end of the milkline Figures 5 and 6. The vacuum fluctuation in the claw with steady milkline vacuum was about 5 kPa (1.5" Hg). This fluctuation is due to the variation of milk flow through the long milk hose. Claw fluctuation may be greater than this in high line milking systems due to the additional vacuum drop caused by lifting milk. Vacuum fluctuations in the milkline less than 2 kPa (0.6" Hg) did not significantly affect the vacuum fluctuation in the claw.

Predicting Fill Depth using Manning's Equation. The measured fill depths during constant air admission are compared to the predicted fill depths using Manning's equation in Figure 7. At low air flowrates Manning's equation under-predicts fill depths (over-predicts milk flowrate) in milklines. This is probably due to the increased frictional effects of fittings and the apparent frictional loss produced by flow disturbances of pulsed milk entry from individual units. Fill depths decreased as the steady air flowrate increased. This indicates that the effects of momentum transfer between the air and liquid are significant in the range of liquid and air flows encountered in milking systems. Manning's equation alone is therefore not a good predictor of milkline flow dynamics.

Transition to Slug Flow: Steady vs Transient Air Admission: The majority of previous studies have been performed using constant liquid and air flow rates. This situation differs significantly from that encountered in milking systems. During milking the air admission can be separated into steady air flow (that entering the system through the air vents in the claw or shells) and transient air flow (that air which enters during unit attachment, liner slips or unit fall-off. The transition between stratified and slug flow was determined for both steady and a combination of steady and transient air flows like those encountered in milking systems. The point of slugging is significantly different for these two situations. The two transition boundaries are shown in Figure 8 for a 73 mm (3 inch) pipe with a 1% slope. Existing flow pattern maps do not accurately predict the onset of slugging in milklines because of this difference in flow conditions.

Effects of Pipe Material and Liquid Properties and Inlet Spacing: Trials were run comparing 48mm (2" nominal) test sections made of PVC and Stainless Steel. Additional comparisons were made between water with the artificial milk solution. When volumetric liquid and air flows were replicated there was no measurable difference in fill depth, vacuum drop or the onset of slugging between either material or liquid. The effect of inlet spacing was examined by varying the spacing of milk entry from pulsating claws from 76 to 245 mm (30 to 96 inches) along the test section. Varying inlet spacing had no significant effect on the fill depth measured in the test section.

Effect of Line Length and Looping vs Dead Ended Lines: There were no significant difference in the onset of slugging between long {29 m, (94 ft) per slope} and short lines {12 m (42 ft) per slope}. There was also no significant difference in the onset of slugging between looped or dead ended lines with the same milk and transient air flow per slope. There were some differences between looped and dead ended lines for steady air admission, however.

Slugging during steady air and milk flow is not normally a concern in milking systems as slugging will occur far earlier under conditions of transient air admission. Transient air admission is always present in modern milking systems during unit attachment. Liner slips also occur commonly and should be accounted for in system design. Thus, the transition to slug flow under transient air admission should be used for design purposes.

Note that all liquid and air flows are expressed on a per slope basis. Dead ended lines have one slope while looped lines have two slopes. Thus, a transient air admission of 100 L/m (3.5 scfm), typical of unit attachment, will produce an air flowrate of 100 L/m (3.5 scfm) per slope in a dead ended line and 50 L/m (1.8 scfm) per slope in a looped line. Looped lines provide a second pathway for air admission to travel to the receiver and effectively half the air flow per slope for unintended air admissions. Looping milklines thus increases their carrying capacity for the same total transient air admission.

Transition to Slug Flow for 48,73 and 98 mm Milklines: The conditions for transition from stratified flow to slug flow are illustrated in Figures 9 to 12 for 48, 60, 73 and 98 mm ID (2", 2.5", 3" and 4" nominal) milklines respectively. The criteria for this transition is a 2 kPa (0.6" Hg) vacuum fluctuation in the milkline. The transition at 0.5, 1.0, and 2.0% slopes for the 48, 73, and 98 mm ID (2", 3", and 4" nominal) milklines are based directly on laboratory measurements. The transition at other slopes and for the 60 mm ID (2.5" nominal) milkline are predictions based on a theoretical flow model confirmed with experimental data.

Effect of Varying Steady Air Flow: The ratio of milk flow to steady airflow used in the experimental conditions was 10 L/m steady air flow to 4.5 L/m milk flow. The effect of increasing the steady airflow was analyzed. Increased steady air admission will add to the total air flow during transient admission, i.e. 100 L/m steady + 50 L/m transient = 150 L/m total air flow, 200 L/m steady + 50 L/m transient = 250 L/m total airflow). Additional steady air flow may be introduced from leaks in the milkline, use of ancillary equipment with air vents such as milk meters, or air vents with higher air admission than 10 L/m.

Regression analysis of the data for all milkline sizes indicated that fill depth was reduced by about 10 percent for each additional 100 L/m of steady air admission. The transition to slug flow increased by about 100 L/m for each 10 percent reduction in fill depth. Thus, increasing steady airflow should have little effect on the risk of slugging for steady air flows up to about 20

L/m per unit.

Design Criteria to Maintain Stratified Flow in Milklines: In addition to line diameter, it is clear that both slope and air flowrate effect the maximum milk flow capacity of milklines. The total milk flow in a milkline is determined by the peak milk flowrate from individual animals, the duration of the peak flow rate, and the rate of attaching milking units. Information has been collected to determine typical peak milk flow characteristics from high producing cows in both Europe and the US (7).

The design flowrates for both transient and steady air admission must also be determined in order to establish a rational design for milklines. Data is also being collected regarding typical steady air flow rates for air vents and transient air flowrates for unit attachment, liner slips and unit fall-off both with and without automatic vacuum shut off valves.

V. Summary and Conclusions

Stratified milk flow, rather than slug flow, is generally accepted as the preferred flow condition in dual purpose milklines. Slug flow conditions almost always induce a transient drop in milkline vacuum greater than 2 kPa (0.6" Hg). Transient vacuum drops caused by slug flow are characterized by a rapid drop in vacuum below the average stable vacuum level in the milkline, followed by rapid recovery when the slug of milk enters the receiver. The key performance indicator of stratified flow is than any transient drop in milkline vacuum should not exceed 2 kPa (0.6" Hg) at the design milk and airflow rates. The design air flowrates should include steady air flow introduced by air vents in the claw, shell or other equipment such as milk meters and transient air flows normally associated with cup attachment and liner slips. Note that this design criteria will not prevent slugging at the high transient airflows encountered during fall-off with units not fitted with automatic vacuum shutoff valves or for poor unit attachment procedures. Occasional transient milkline vacuum fluctuations in excess of 2 kPa (0.6" Hg) will have little or no effect on milking performance.

Vacuum fluctuations in the claw did not increase until the milkline vacuum fluctuation exceeded 2 kPa (0.6" Hg). Vacuum fluctuations in the milkline near the receiver were highly correlated with vacuum fluctuations at the distal end of the milkline. Thus a slug occurring at any point in the pipeline is likely to produce a 2 kPa (0.6" Hg) vacuum fluctuation in the entire milkline. Vacuum fluctuations in the receiver were not affected by milkline slugs.

The length of milkline had little of no effect on onset of slugging or degree of vacuum fluctuation. Little difference was observed between looped and dead-ended lines in the effects of transient air admission for the same air and milk flow per slope. Some differences were observed for steady air admission.

Transient air admission has the dominant effect on milkline slugging. Transient or "unplanned" air admission of the type commonly occurring in milking systems induced slugging at much lower air and liquid flowrates compared with steady air admission. Previously used flow pattern maps are therefore not reliable predictors of the transition to slug flow.

At low air flowrates Manning's equation under-predicts fill depths (over-predicts milk flowrate) in milklines. This is probably due to the increased frictional effects of fittings and the apparent friction produced by kinetic disturbances of milk entering the milkline from individual units. Fill depths decreased as the steady air flowrate increased. This indicates that the effects of momentum transfer between the air and liquid are significant in the range of liquid and air flows encountered in milking systems. Manning's equation is therefore not a good predictor of milkline flow dynamics. Increasing milkline slope greatly increases the effective carrying capacity of the milklines.

Table I. Theoretical Prediction of Fill Depth and Frictional Loss in Milklines.

Milkline Internal Diameter = 98 mm

%Slope	Units	Vsa	Vsm	L(m)
2.0	67	3.5	0.59	519
1.5	58	3.1	0.51	644
1.0	47	2.6	0.42	873
0.8	43	2.4	0.38	989
0.5	33	2.0	0.29	1414

Milkline Internal Diameter = 73 mm

%Slope	Units	Vsa	Vsm	L(m)
2.0	30	3.3	0.48	403
1.5	26	3.0	0.41	482
1.0	21	2.6	0.33	618
0.8	19	2.5	0.30	691
0.5	15	2.2	0.24	882

Milkline Internal Diameter = 60 mm

%Slope	Units	Vsa	Vsm	L(m)
2.0	18	3.5	0.42	292
1.5	15	3.2	0.35	352
1.0	12	2.8	0.28	433
0.8	11	2.7	0.26	467
0.5	9	2.5	0.21	548

Milkline Internal Diameter = 48 mm

%Slope	Units	Vsa	Vsm	L(m)
2.0	10	4.1	0.37	177
1.5	8	3.7	0.29	209
1.0	7	3.5	0.26	229
0.8	6	3.3	0.22	252
0.5	5	3.1	0.18	279

Maximum Fill Fraction = 0.5
Steady Air flow Rate per unit = 10 l/m
Transient Air Flowrate per slope = 120 l/m
Units = Maximum number of units per slope assuming milk flowrate of 4 lpm/unit.
Vsa = Superficial air velocity (m/s), (volumetric air flowrate/total pipe area).
Vsm = Superficial milk velocity, (m/s), (volumetric milk flowrate/total pipe area).

L = Maximum pipe length per slope (m) for 3 kPa vacuum drop.

VI. References

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Figures

As a preliminary estimate, the transition to slug flow was determined using predicted superficial air and milk velocities and a commonly accepted flow pattern map (Figure 1).

The experimental layout is illustrated in Figure 2.

Examples of dynamic fill depth and milkline vacuum measurement is illustrated in Figures 3 and 4.

The vacuum fluctuation measured in the milkline just downstream from the last milk inlet is plotted against the vacuum fluctuations in the claw, at the distal end of the milkline and the receiver in Figures 5 to 7.

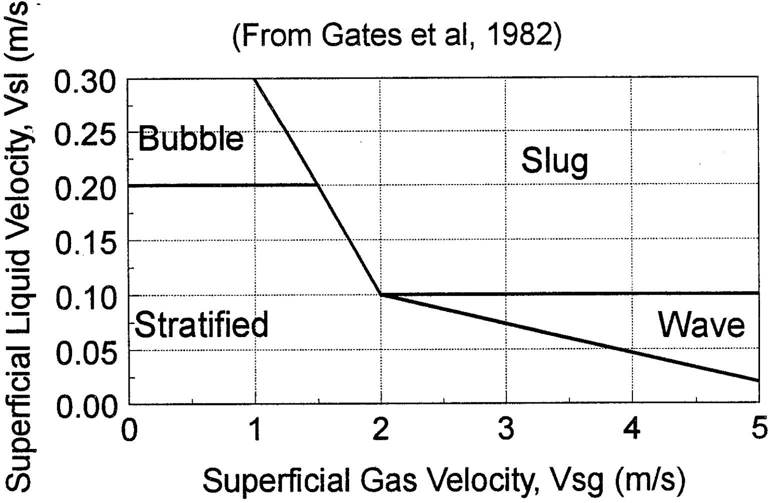
The measured fill depths during constant air admission are compared to the predicted fill depths using Manning's equation in Figure 8.

The two (steady, transient) transition boundaries are shown in Figure 9 for a 73 mm (3 inch) pipe with a 1% slope.

The conditions for transition from stratified flow to slug flow are illustrated in Figures 10 to 12 for 48, 73 and 98 mm ID (2", 3" and 4" nominal) milklines respectively.

The predicted transition for a 60 mm (2.5" Nominal) line is also shown in Figure 13.

Figure 1. Two Phase Flow Pattern Map



(From Gates et al, 1982)

Figure 2. Experimental Setup.

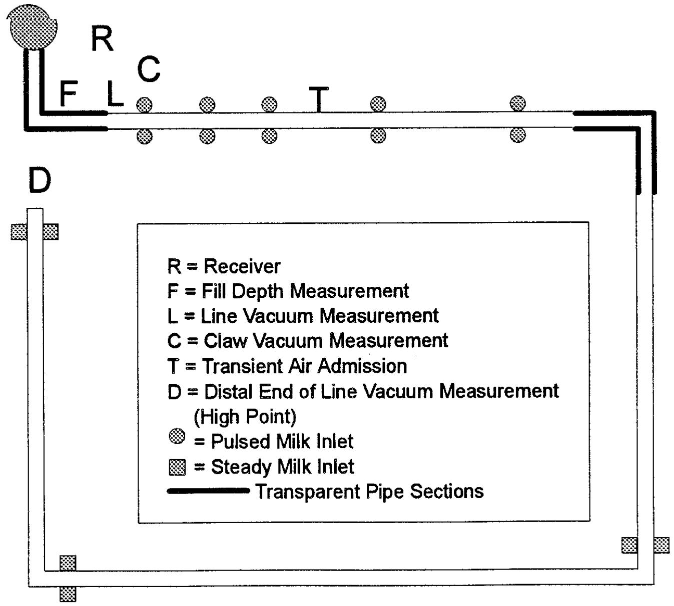


Figure 3. 73 mm (3") Milkline, 1% Slope

58.5 lpm Milk, 130 lpm Steady, 100 lpm Trans Air

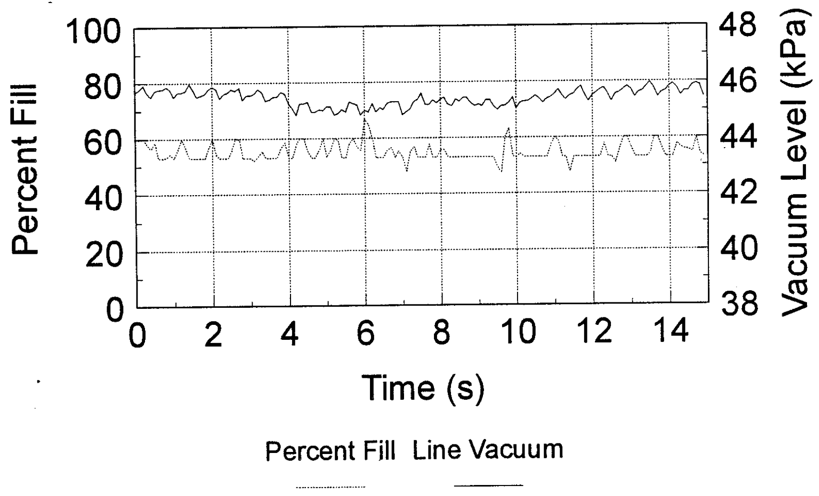


Figure 4. 73mm (3") Milkline, 1% Slope

67.5 lpm Milk, 150 lpm Steady, 200 lpm Trans Air

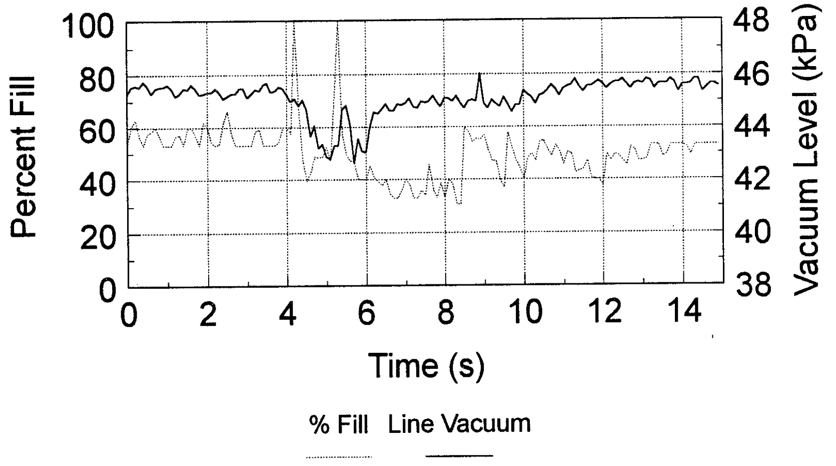


Figure 5. Milkline Vacuum Fluctuation Versus Claw Vacuum Fluctuation.

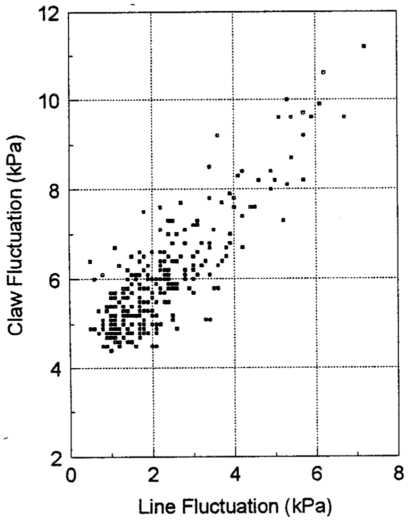


Figure 6. MilkLine Fluctuation Near Receiver Vs Distal End of Milkline Fluctuation.

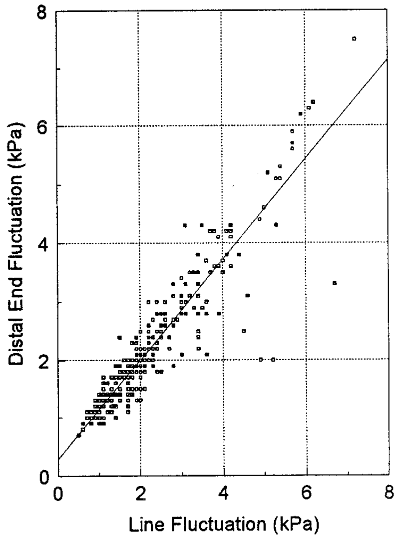


Figure 7. Measured Fill Depth vs Mannings Eqn. 73 mm (3") Milkline, 1% Slope

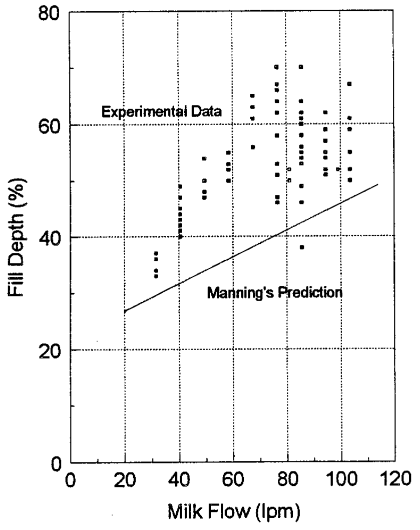
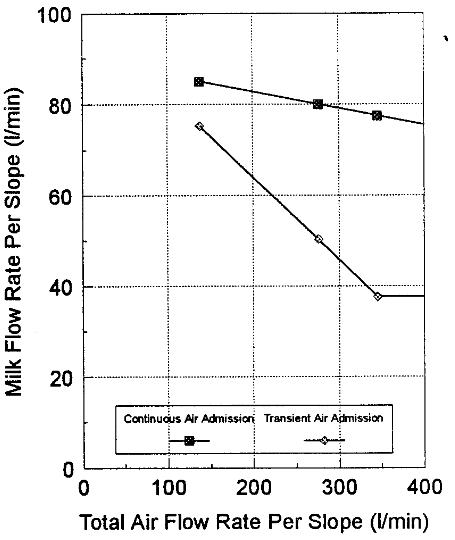


Figure 8. Transition to Slug Flow 73 mm (3") Milkline, 1% Slope



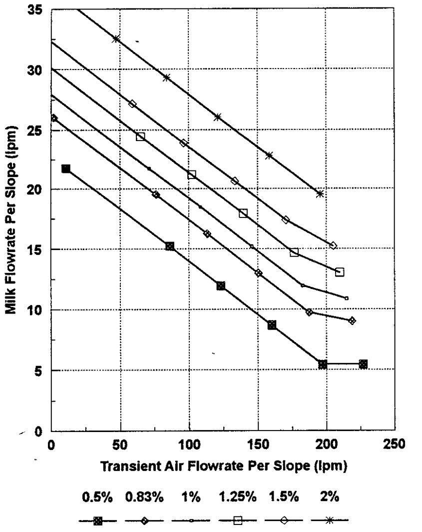


Figure 9. Transition to Slug Flow
48 mm (2") Milkline

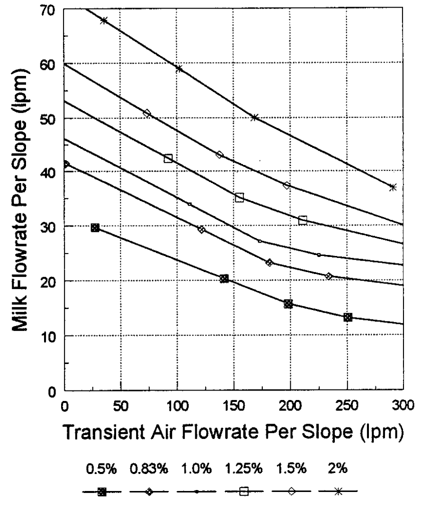


Figure 10. Transition to Slug Flow
60 mm (2.5") Milkline

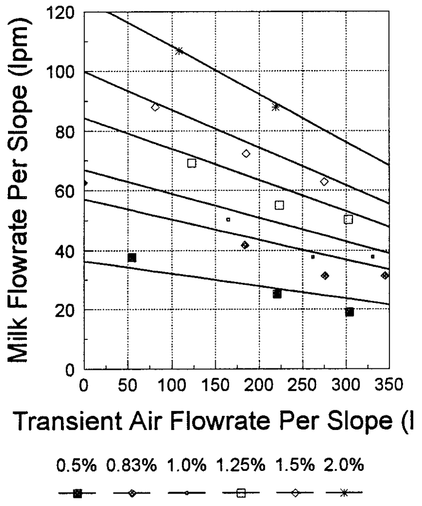


Figure 11. Transition to Slug Flow
73 mm (3") Milkline

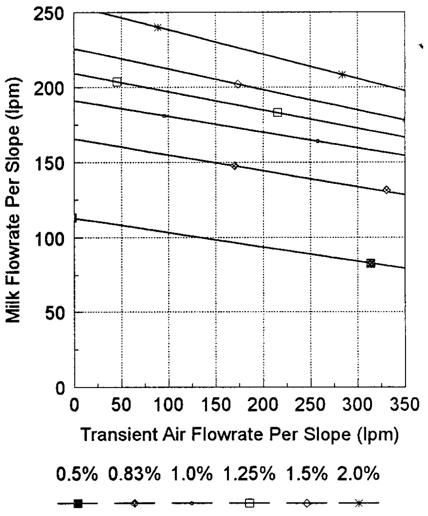


Figure 12. Transition to Slug Flow
98 mm (4") Milkline