TRANSITION BETWEEN STRATIFIED FLOW AND SLUG FLOW CONDITIONS IN MILKLINES

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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.

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.

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 common flow patterns encountered in two phase flow are illustrated in Figure 1. The transition to slug flow for the theoretical analysis was determined using predicted superficial air and milk velocities and the commonly accepted flow pattern map illustrated in Figure 2. 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 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 <u>no slugging</u> 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.

<u>Experimental Study</u>

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 for the expected maximum fill depths and slugging conditions. Details of the experimental apparatus, procedures and results are given in Reinemann et al, 1992 (8).

Experimental Results

Milkline Fill Depth and Vacuum Fluctuation: 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 and Claw and Receiver: 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. Vacuum fluctuation at the distal end of the milkline were highly correlated with those in the milkline near the receiver. Vacuum fluctuations in the receiver were not affected by vacuum fluctuation in the milkline.

Predicting Fill Depth using Manning's Equation: 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 versus 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. Existing flow pattern maps do not accurately predict the onset of slugging in milklines because of this difference in flow conditions.

Effects of Inlet Spacing: 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 was 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 they effectively halve the air flow per slope for unintended air admissions. Looping milklines thus increases their carrying capacity for the same total transient air admission.

Design Criteria to Maintain Stratified Flow in 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, Stewart et al, 1993 (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 was 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.

Transition to Slug Flow for 48, 60, 73 and 98 mm Milklines: The conditions for transition from stratified flow to slug flow are illustrated in Figures 3 to 6 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.

Summary and Conclusions

Increasing milkline slope greatly reduces the risk of slug flow and increases the effective carrying capacity of milklines by reducing average fill depth for any given milk flowrate.

Occasionally, a vacuum drop of 2 kPa (0.6" Hg) or more results from frictional losses due to high air flowrate in unusually long milklines. Under all but the most extreme conditions, however, milkline length is not limiting and is not an important design factor for specifying milkline size.

Transient air admission has a marked effect on milkline slugging because the relative velocity of air to liquid is the dominant factor influencing the transition from stratified flow to slug flow. Therefore, "unplanned" transient air admission (the intermittent air flows associated with cup changing, liner slip and cup fall-off) induces slugging at much lower air and liquid flowrates, compared with the effects of steady air admission (the air entering the milkline from air vents in the cluster or in some milk meters, and from leaking fittings or milk hoses).

Higher levels of continuous air admission should have little effect on the risk of slugging, for any given transient air flowrate, because mean fill depth in the milkline decreases as the steady air flowrate increases (within the normal range of practical interest).

Transient vacuum drops less than 2 kPa (0.6" Hg) in the milkline, due to "unplanned" air admission through one cluster, have little or no effect on the normal cyclic vacuum changes in other clusters. However, vacuum fluctuations in the claw are usually increased whenever the milkline vacuum fluctuation exceeds 2 kPa (0.6" Hg).

A design guideline of 100 L/min (3.5 scfm) transient air admission per slope for a looped milkline, or 200 L/min (7 scfm) for a dead-ended line, appears to be a reasonable allowance for liner slip and cup changing for most operators and conditions. However, these guidelines will not prevent slugging in the milkline when a cluster falls or is kicked off (unless claws with effective, automatic shut-off valves are used) or when cups are attached or removed carelessly, with no attempt to limit air entry.

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