TRANSITION FROM STRATIFIED TO SLUG FLOW IN MILKLINES

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ABSTRACT. The results of an experimental study of two-phase flow characteristics in dual-purpose milklines under milking conditions is presented. This project was undertaken to provide data for the revision of United States and international standards for sizing milklines in milking machine installations. The experimental setup and conditions are described. The key performance indicator of stratified flow is that vacuum in the milkline should not fall more than 2 kPa below the receiver vacuum during milking. Design criteria to meet this performance guideline should include milkline diameter and slope as well as expected peak milk flow, and steady and transient air flow rate per slope.

Keywords. Milklines, Milking machines, Milk flow rate, Airflow rate.

In both the United States 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. Dual-purpose milklines are those which carry both milk and air admitted through the claw during milking. Stratified, gas-liquid flow occurs in horizontal or slightly inclined pipes when the liquid phase fills the bottom portion of the pipe and the gas phase has an unobstructed flow path in the upper portion of the pipe. Slug flow occurs when the liquid phase completely fills the cross-section of the pipe and impedes the flow of the gas phase.

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 U.S. standard (IAMFES, 1990) specifies a minimum slope, but does not consider any effects of varying slope. The present ISO standard (ISO, 1983) incorporates a correction for length but not slope. Gates et al. (1981, 1982) showed by experimental and theoretical analyses that carrying capacity of milklines is increased by increasing diameter and/or slope.

The appendix to 3-A Accepted Practice 606-03 (IAMFES, 1990) is widely used for specifying milkline carrying capacity in the United States. These recommendations originated from a 1978 Californian guideline (Smith et al., 1978) which limited the number of milking units to the square of the nominal pipe diameter in inches, e.g., a 48-mm ID (2-in. nominal) line could have a maximum of four units per slope. Although 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 International (ISO, 1983) and British (BSI, 1988) guidelines for the carrying capacity of milklines are based on a maximum acceptable vacuum drop of 3 kPa due to friction over the milkline length. This criterion does not account for the fact that slug flow might occur because of the combined effects of high fill depth and high air velocity. If slugging does occur, the method of calculating frictional loss is flawed. However, occasional transient milkline vacuum fluctuations in excess of 2 to 3 kPa will have little or no effect on milking performance (Mein et al., 1993).

Both the ISO and British standards adjust the allowable number of units for the total length of the milkline. 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 short milklines in milking parlors. Conversely, U.S. standards may be inadequate for long milklines with little slope in stanchion barns (Mein et al., 1993). The existing ISO and British guidelines allow more units per slope than U.S. standards for dead-ended milklines that are more than about 60-m long or for looped milklines 150 m or more in total length.

Measurements by Spencer (1991), on one farm, indicate that up to 16 units per slope might be acceptable on a short, looped 73-mm ID milkline. However, this study was done on one slope of a looped line and no quantitative indication of milk or airflow rates was given. More extensive studies were needed to develop rational criteria to revise and reconcile present ISO, 3A, and American Society of Agricultural Engineers (ASAE, 1992) standards and guidelines.

This article reports results of an experimental study of two-phase flow characteristics in dual-purpose milklines under simulated milking conditions. The objectives of this study were to determine the air and milk flow rates for transition from stratified to slug flow in dual-purpose milklines under conditions typical of milking practice and to measure the vacuum fluctuations produced by slugging in milklines.

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MATERIALS AND METHODS

An experimental apparatus was constructed to study the transition from stratified to slug flow conditions for milking lines. Milking lines of 48-, 73-, and 98-mm internal diameter sloped at 0.5, 1.0 and 2.0% were tested. Configurations included both looped and dead-ended lines and line lengths of 12 and 29 m/slope. The experimental layout is illustrated in figure 1. The experimental conditions and measurement points were chosen to replicate a worst-case scenario for the expected maximum fill depths and slugging conditions.

Commercially available milking system fittings including elbows, milk/wash valve, and receiver inlets were used together with straight PVC-pipe sections for the measurements. Internal diameter of PVC pipe were within 0.1 mm of standard, commercial stainless steel milking lines. Initial liquid and airflow tests were made to compare stainless steel pipe sections with PVC.

A synthetic milk solution was prepared, which at 20°C had viscosity, density, surface tension, and foaming characteristics similar to fresh milk at 37°C. The mixture was adapted from a formula suggested by Mein and Whittlestone (1965) and consisted of: 94% water by volume, at 20°C 6% glycerol by volume 20 ppm California Mastitis Test reagent 20 ppm Carboxy-methyl-cellulose This fluid was used for most of the trials. Comparison trials were made with plain water at room temperature to determine the effect of milk foaming on the free space available for airflow, interfacial shear stress, and slug formation.

Liquid flows were increased in increments of 4.5 L/min which is representative of the peak flow rate from one cow (Stewart et al, 1993). When two-slope, looped lines were tested, liquid flows were the same on both slopes. Liquid entered the section of milkline nearest the receiver through commercial milking units attached to artificial udders. The four individual teats of the artificial udders were fitted with flap valves which respond to pulsation to produce pulsed milk flow as in actual milking practice. Alternating pulsation at 60 cycle/min and 16 mm diameter long milk tubes were used throughout the experiment. Each artificial udder was fitted with a Dwyer variable area flow meter with 37 L/min range (1% FS accuracy) to monitor the average liquid flow rate. Up to four units could be attached to the section of milkline nearest the receiver. Additional liquid was introduced at steady flow rates into upstream sections of the milkline through Dwyer variable area flow meters with 37 L/min range (1% FS accuracy).

Air enters milking lines in two ways during milking. A steady flow of air is introduced from air vents in clusters and some types of milk meters. Air is also admitted intermittently when units are attached to the cow, or when cups slip or fall off. Typical durations for these events are 0.1 s for slips, 1 s for attachment, and more than 10 s when unit falls if claws are not fitted with automatic vacuum shut-off valves. Both steady and transient airflows were admitted to the milkline in this experiment. Steady state airflow was introduced in the ratio of 10 L/min of air per 4.5 L/min of liquid, which is representative of air to milk flow ratio under peak flow conditions for fast milking cows. The units used to pulse milk flow were fitted with standard air vents for this purpose. Any additional steady state air admission required was introduced at the distal end of the milk line through one of three Dwyer variable area flow meters with ranges 25, 250, and 1200 L/min (all 1% FS accuracy) depending on the amount of air required.

Transient air was admitted through a Dwyer variable area with 1200 L/min range (1% FS accuracy) and into a milk inlet 1-m upstream of the milk inlet nearest the receiver. Transient airflow rates ranged from 50 L/min to 500 L/min per slope. Transient airflow was switched on and off with a solenoid valve. Transient air was admitted for a period of 6 s after allowing the steady state air admission and liquid admission to reach equilibrium conditions.

Vacuum was recorded in the claw bowl, in the milkline 1 m downstream of the milking unit closest to the receiver, at the distal end of the milkline, and in the receiver. Omega model PX236 vacuum transducers (range = 0-100 kPa gage vacuum, repeatability ±0.025% FS, response time = 1 ms) were used to monitor system vacuum. The vacuum transducers were calibrated against a mercury column before the experiments began and were recalibrated weekly during the experiment.

Milking line fill depth was measured just upstream from the elbow nearest the receiver (1.5 m downstream of the nearest milk inlet). This measurement location was chosen as it was the point of maximum fill depth. Visual inspection showed a local increase in fill depth about 1 m upstream and 2 m downstream of pulsed milk entry through a milk inlet. Pipe fill was also reduced by up to 6 mm when passing through an elbow. Thus, the location just downstream of a milk inlet and just upstream of an elbow produced the maximum fill depth.

The sensor used to measure fill depth was a specially constructed 2-mm-thick printed circuit board with a series of 1-mm conductive elements spaced at 3-mm intervals (Grasshoff and Reinemann, 1993). This sensor was mounted across the vertical diameter of a section of clear acrylic pipe. A 5-V excitation voltage was applied to the bottom element. The voltage threshold level indicating contact was set at 1.5 V so that the sensor responded to liquid but not foam. The sensor was tested statically and dynamically by measuring fill depth with a 1-mm resolution scale held behind the transparent pipe as a reference. The response time of the sensor was less than

Figure 1–Experimental system configuration.
1 ms. The sensor produced from 1 to 3 mm increase in fill depth when compared to the same liquid flow in the absence of the sensor. The greatest error (up to 3 mm over reading) occurred at high liquid flow rates and low airflow rates. Visual observation and high speed photographs indicated that the liquid surface was essentially horizontal, perpendicular to the direction of flow for the range of air and liquid flows tested. Waves of 5 to 30 mm in length produced irregularities parallel to the direction of flow, however.

The four vacuum sensors and 16 fill-depth probes interfaced with a computer-based data acquisition system (Kiethly DAS 20/EXP-GP). An analog output channel from this system was also used to control the transient air admission valve. Input channels were scanned at a rate of 100 Hz and maximum fill depth and minimum vacuum values stored and displayed every 0.1 s.

**EXPERIMENTAL OBSERVATION METHOD**

Liquid and airflow rates were adjusted in steady state conditions with the system under 45.5 kPa gage vacuum. The system was allowed to stabilize for 1 to 2 min. Each observation began with a 4-s recording of the stabilized system with liquid flow and only steady airflow. The transient air was then introduced for a period of 6 s followed by a 5-s recording of system parameters after transient airflow was stopped. The total duration was 15 s for each series of simultaneous recordings of vacuum level at four locations and fill depth at one location.

Measurements were made with 0, 50, 100, 200, and 300 L/min of transient air admission for each pipeline configuration. Liquid and airflows were increased in increments of 4.5-L/min liquid with a ratio of 10-L/min steady air: 4.5-L/min liquid until slugging occurred. Following is an example of the air and liquid flow settings for a two-slope, looped, 73-mm milkline arranged to simulate 14 units/slope: Entering the sections nearest the receiver; four pulsating units/slope with 4.5-L/min liquid flow and 10-L/min steady airflow per unit for a total of 18-L/min/slope liquid flow and 40-L/min/slope steady air admission through the claw air vents. Transient air of 200 L/min was admitted into this section for 6 s. Entering each of the other three pipe sections: 18-L/min/slope liquid (not pulsed). Entering the distal end of the milkline: 200-L/min/slope steady airflow, the equivalent steady airflow for 10 units/slope on two slopes. Total flow per slope: 63-L/min liquid flow, 140-L/min steady air admission, and 100-L/min transient air admission.

**RESULTS AND DISCUSSION**

**MILKLINE FILL DEPTH AND VACUUM FLUCTUATION**

The data presented in figure 2 are typical of a stratified flow condition before slugging occurs. Several characteristics of milkline flow are apparent from this graph. A cyclic variation in fill depth due to the pulsed entry of milk from the long milk tube into the milkline is apparent throughout the test. These pulses of milk produce waves which persist for several meters downstream of the inlet. The existence of these waves measured with the fill-depth sensor was confirmed visually. Average fill depth decreased by about 5% and vacuum fell by about 1 kPa during the period of increased airflow. The vacuum drop was caused by increased frictional losses due to the increased airflow. The fill depth was reduced because of increased momentum transfer between the air and liquid.

The data presented in figure 3 are typical of a condition when slugging was induced by the combined effects of steady and transient air admission. Two slugs were produced between 4 and 6 s. A large wave occurred between 8 and 10 s. The transient vacuum drop associated with the slugs was about 2.5 kPa. The fill depth remained low after the slug had passed for two reasons. Firstly, the slug removed liquid from the line. Secondly, the higher transient airflow increased momentum transfer from the air to the liquid.

At low slopes and low transient air admission, the transition to slug flow was not distinct. As airflow is increased, the waves produced by pulsed milk entry enlarge 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.

A milkline vacuum drop of more than 2 kPa below the receiver vacuum provided a reasonably consistent indication of slug formation. The effects of vacuum fluctuation due to regulator response can be eliminated by subtracting the vacuum fluctuation measured in the receiver from the vacuum fluctuation measured in the milkline.

In some cases near the transition zone, large waves occurred and appeared, by visual inspection, to be slugs. However, they produced fluctuations less than 2 kPa because they did not fill the entire pipe cross-section. In lines with low slope, low levels of transient air admission, and high liquid flow, slowly moving slugs formed which produced vacuum fluctuations less than 2 kPa. These phenomena occurred for both looped and dead-ended milk lines for the same milk and airflows per slope.

**Vacuum Fluctuations in the Milkline, Claw, and Receiver**

The vacuum drop in the milkline was plotted against the vacuum fluctuations in the claw (fig. 4), and the vacuum drop at the distal end of the milkline (fig. 5). These graphs are for the same series of tests in a 73-mm milkline. The fluctuation in the claw was taken as the maximum minus the minimum vacuum over the test period. Mean vacuum fluctuation in the claw with steady milkline vacuum was about 5 kPa. This fluctuation is due to cyclic opening and closing of the teatcup liners and 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 drop in the milkline less than 2 kPa did not significantly affect the vacuum fluctuation in the claw (fig. 4). The vacuum drop in the distal end of the milkline due to transient air admission and slugging was closely correlated with vacuum drop in the milkline near the receiver (fig. 5).

**Transition to Slug Flow: Steady vs. Transient Air Admission**

The majority of previous two-phase flow studies have been performed using constant liquid and airflow rates. This situation differs significantly from that encountered in milking systems. During milking, the air admission can be separated into steady airflow (that entering the system through the air vents in the claw or shells) and transient airflow (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 airflow and a combination of steady and transient airflows like those encountered in milking systems. The transition to slug flow was found to be significantly different for these two situations. The two transition boundaries are shown in figure 6 for a 73-mm ID pipe with a 1% slope. Existing flow pattern maps, developed for steady flow conditions, do not accurately predict the onset of slugging in milklines with transient airflow.

In figures 6 through 9, liquid and airflow rates below and to the left of individual transition lines will produce stratified flow conditions. Liquid and airflow rates above and to the right of individual transition lines will produce slug flow conditions.
EFFECTS OF PIPE MATERIAL, LIQUID PROPERTIES, AND INLET SPACING

Milklines of 48-mm ID, PVC, and stainless steel were compared. Additional comparisons were made using water and the artificial milk solution. When volumetric liquid and airflow rates were replicated there was no measurable difference in fill depth versus flow rate, vacuum drop, or the onset of slugging between pipe materials or test liquids. Pulsed milk inlets were spaced at intervals of 0.6, 1.2, or 2.4 m along the test section. Varying inlet spacing had no significant effect on the transition to slug flow or fill depth measured in the test section.

EFFECT OF LINE LENGTH AND LOOPED VS. DEAD-ENDED LINES

There was no significant difference in the onset of slugging between lines ranging in length from 12 m and 29 m/slope. There was also no significant difference in the onset of slugging between looped or dead-ended lines with the same milk flow and transient airflow per slope.

For steady air admission there were some differences observed between looped and dead-ended lines. 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 almost always occurs 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 conditions of expected rates of transient air admission should be used for design purposes.

Looping milklines increases their milk carrying capacity for any given slope because looped lines provide a second pathway for unintended transient air admission to travel to the receiver. Therefore, the transient airflow per slope for unintended air admissions is reduced. The airflow rate per slope will be inversely proportional to the resistance in each flow path.

TRANSITION TO SLUG FLOW FOR MILKLINES

The transition lines indicating the boundary between stratified flow and slug flow are illustrated in figures 7 through 9 for 48-, 73-, and 98-mm ID milklines, respectively. The criteria for this transition is a 2-kPa drop in milkline vacuum below receiver vacuum.

DESIGN CRITERIA TO MAINTAIN STRATIFIED FLOW IN MILKLINES

In addition to line diameter, it is clear that slope, airflow rate, and the way that air is introduced (steady, transient, or a combination) must be taken into account to determine the maximum milk flow capacity of milklines. The total milk flow in a milkline is determined by the peak milk flow rate from individual animals, the duration of the peak flow rate, and the rate of attaching milking units. Information on typical peak milk flow characteristics from high producing cows in both Europe and the United States has been published (Stewart et al, 1993). The range of steady airflow rates for air vents and transient airflow rates for unit attachment, liner slips, and unit fall-offs both with and without automatic vacuum shut-off valves for commercial milking units has been documented (Mein et al., 1994; Spencer, 1978).
SUMMARY AND CONCLUSIONS

Stratified milk flow, rather than slug flow, is generally accepted as the preferred flow condition in dual-purpose milklines. The key performance indicator of stratified flow is that vacuum in the milkline should not fall more than 2 kPa below the receiver vacuum during milking. Slug flow conditions almost always produce a milkline vacuum drop more than 2 kPa below receiver vacuum. Vacuum fluctuations in the receiver are not affected by milkline slugs.

Vacuum drop in milklines, caused by slug flow, are characterized by a rapid drop in vacuum below the average stable vacuum level in the receiver, followed by rapid recovery when the slug of milk enters the receiver. Transient air admission has a marked effect on milkline slugging. Transient or "unplanned" air admission of the type commonly occurring in milking systems induces slugging at much lower air and liquid flow rates compared with steady air admission. Vacuum fluctuations in milking units increase whenever the milkline vacuum drop exceeded 2 kPa.

Increasing milkline slope greatly increases the effective carrying capacity of the milklines. Occasionally, a vacuum drop of 2 kPa or more results from frictional losses due to high airflow rate in unusually long milklines. Under all but the most extreme conditions milkline length is, therefore, not limiting and is not an important design factor for specifying milkline size. Looping milklines increases their milk carrying capacity for any given slope because looped lines provide a second pathway for unintended transient air admission to travel to the receiver.

Design criteria to meet the proposed performance guideline of 2 kPa should include milkline diameter and slope as well as expected peak milk flow, steady, and transient airflow rate per slope. The designed airflow rate should include steady airflow introduced by air vents in the claw, shell, or other equipment such as milk meters, steady air leaks in the milk flow path, and transient airflows normally associated with cup changing and liner slips. These design criteria will not prevent slugging at the high transient airflows produced by exceptionally poor unit attachment procedures or by unit fall-off unless milking units are fitted with automatic vacuum shut-off valves. Unit falloffs are rare events, however, and excessive air admission during attachment can be avoided by good milking procedures.

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