TWO-PHASE CLEANING FLOW DYNAMICS IN AIR INJECTED MILKLINES

Douglas J. Reinemann, Assistant Professor
Agricultural Engineering Department, University of Wisconsin - Madison

Albrecht Grasshoff, Senior Scientific Councillor
Institute for Process Engineering, Federal Center for Dairy Research, Kiel, Germany

Published in the 1994 Transactions of the ASAE, Vol. 37(5): 1531-1536.

ABSTRACT: The results of a study of slug flow dynamics in air injected milkline Clean-In-Place (CIP) systems are presented. Experimental measurements of slug velocity, slug length, and air admission rate made on 48 mm, 73 mm and 98 mm ID milklines are presented. The air injector must be left open long enough for the slug to travel the entire milkline in order to ensure contact between the slug and all pipe surfaces. Optimal mechanical cleaning action is produced by slug velocities of 7 to 10 m/s. The rate of air admission through the air injector should be controlled to produce superficial air velocity of 8 to 12 m/s to achieve these slug velocities.

TWO PHASE CLEANING FLOW DYNAMICS IN AIR INJECTED MILKLINES

INTRODUCTION

Milkline cleaning is accomplished by a combination of chemical, thermal and mechanical actions. Chemical and thermal actions are provided by the hot detergent, acid and sanitizer solutions contacting pipe walls. Mechanical action is provided in clean-in-place (CIP) systems by the turbulent wall shear stress created by circulating the cleaning solutions.

Air admission is commonly used when cleaning modern milking systems. The admission of air reduces the volume of liquid in the milkline and increases the liquid flow velocity when compared to fully flooded operation without air admission. The presence of one or more 'slugs' of liquid characterize this flow. Slugs of water and air move co-currently through the milkline at first moving uphill to the high point of the system then downhill returning to the receiver. Milkline slopes generally range from 0.5 to 1.5 %. The milkline is partially filled by a liquid layer ahead of and behind the slug which moves in the same direction as the slug but at a lower velocity. A more detailed description of the design and function of milking system cleaning circuits is presented in MMMC (1993) and Reinemann and Book (1994).

Current recommendations for milking system CIP design are not well defined and vary widely. Regulations in the United Kingdom (BSI, 1988) specify a minimum vacuum pump capacity of $8(10)^{-3}$ m^3/s for any clean in place facility, with no modification for size of milkline. A minimum circulation rate of liquid through recorder jars of $7.5(10)^{-5}$ m^3/s per unit, of which at least $2.5(10)^{-5}$ m^3/s should flow through the cluster assembly, with wash line size specified to achieve this flow rate are also recommended. No recommendations are made for dual purpose milking pipeline systems. Nordic recommendations state that the pump capacity for in place cleaning and disinfection shall be sufficient to reach slug velocities of 10 m/s in the milkline (NDA, 1988). For this purpose the effective reserve for cleaning (ERC) should be $9.2(10)^{-3}$ m^3/s for 48.6 mm ID and $2.1(10)^{-2}$ m^3/s for 72.9 mm ID milklines. Recommendations are not given for the location or method of air admission. Canadian guidelines indicate that air admission is required but give no details as to the location or volume of air admission (Agriculture Canada, 1990). The 3A Accepted Practices, commonly used in the US as recommendations, do not specify vacuum pump requirements or system details for cleaning but do specify a minimum vacuum pump capacity of 1.7(10)-3 m^3/s for any system (IAMFES, 1990). The US Milking Machine Manufacturers Council cites velocity as a requirement for successful cleaning but gives no indication of adequate velocity (MMMC, 1993). In general, the basis for these CIP recommendations are not indicated, no indications are given for location of air admission, or timing of air admission cycles, and no provisions are made for different system geometries or length of lines.

Two-phase, air-water flows have been widely studied and described in comprehensive reviews (Hetsroni, 1982; Govier and Aziz, 1972; Wallis, 1969). Air injected milking system flow differs from that encountered in most two phase flow literature in several respects. First, the flow is unsteady. Liquid enters the milkline periodically at a low velocity and a slug is formed by periodic air admission. This slug is rapidly accelerated and changes length as it travels. Second, there is usually only 1 slug in the milkline at any one time. This differs from fully developed slug flow in which there are a series of slugs moving through the line. Third, the system is under partial vacuum rather than under pressure. Only one study of air injected milkline cleaning dynamics has been previously reported (Tragardh, and Von Bockelmann, 1980). The study was done in a 34 mm diameter pipe and used steady air admission rather than the cyclic air admission used in modern milking system.

This study was undertaken to provide information to improve the performance of air injected CIP systems in large diameter milklines. The specific objectives of the study were to:

1) Characterize the length, velocity and mechanical cleaning action produced by a slug flow in air injected milklines.
2) Develop recommendations for air admission rates and system control to assure effective cleaning of milklines.

EXPERIMENTAL APPARATUS AND METHODS

The layout, dimensions, internal volume, and operating characteristics of the test system were representative of modern milking systems. The test loop consists of two straight pipe sections of equal length connected by a 180° U-bend (Figure 1). Test loops composed of 72 m of 73 mm ID pipe, 51 m of 48 mm ID pipe and 51 m of 98 mm ID pipe were tested. The milkline loop was uniformly sloped at 1% from the U bend (high point of system) to a .027 m^3 receiver jar. A manually operated gate valve was installed in one pipe at its junction with the receiver jar. This valve was closed during cleaning to direct the liquid and air through the entire milkline, traveling first uphill to the system high point and then downhill back to the receiver. Transparent pipe sections were installed at the beginning and the end of the milkline for flow observation. All experiments were performed with air and plain tap water at room temperature of approximately 20^oC.

Air and water were introduced to the milkline near the gate valve through a 35 mm ID pipe. The admission of air and water was controlled by a pneumatically actuated air injector mounted on the water supply line near its junction with the milkline. When the air injector was closed, water was drawn from the wash vat into the test loop. When the air injector was opened water flow was stopped, or slowed considerably, and air was drawn into the milkline. The volume of water and air entering the system were controlled by the time the air injector was closed and open. The air flow rate during air admission was controlled by orifices mounted in the air injector. Water and air were collected and separated in the receiver. Water was returned to the wash vat by a centrifugal pump mounted on the bottom of the receiver. Air was removed by a vacuum pump through the sanitary trap. The sanitary trap incorporated a ball check valve to prevent water from being drawn into the vacuum pump.

The vacuum pump was a positive displacement liquid-ring pump with a maximum capacity of $5.2(10)^{-2}$ m^3/s at 50 kPa vacuum. The system vacuum was controlled with a commercial milking system vacuum regulator mounted on a 70 mm ID main air line between the vacuum pump and the sanitary trap. All test were performed at 47 kPa gage vacuum (47 kPa below atmospheric pressure). A 0.19 m^3 PVC distribution tank and 72 m of 70 mm ID PVC pulsator air line were also connected to the system.

Two dynamic fill depth sensors were mounted in a movable transparent pipe section with a separation distance of 1.0 m. The fill depth sensors were made of 2 mm thick printed circuit board with a series of 1 mm conductive elements spaced at 3 mm intervals (Grasshoff and Reinemann, 1993). The conductive elements were coated with a silicon waterproofing and insulating compound with the exception of a 1 mm strip on the leading edge of the sensor. This sensor was mounted across the vertical diameter of the pipe. A 10 V excitation signal was applied to the common element on the back of the card. The excitation signal was switched from +10 to - 10 V with a frequency of 1 Hz to avoid polarization of the electrodes. The voltage measured across the sensor elements was greater than 1.5 V (+/- depending on the polarity of the excitation voltage) when liquid was in contact with the element. The sensor was tested statically and dynamically by measuring fill depth with a scale held behind the transparent pipe as a reference.

Slug velocity was determined by dividing the probe separation (1 m) by the time required for the leading face of the slug to travel between the probes. The slug length was then calculated by multiplying the time that the top electrode was in contact with the slug by the slug speed. High speed photographs showed that the face of the slug was quite distinct while the tail of the slug was long and ill defined. Slug velocity and length measurements were repeatable to within 5%

and 15% respectively for a given air injector setting.

Pressure transducers (Omega model PX236, range =0 to 100 kPa gage vacuum, repeatability +/- 0.025 % of full scale, response time =1 ms) were mounted at the beginning, midpoint and end of the pipe loop and in the movable test section. The vacuum transducers were calibrated against a mercury column before the experiments began and were re-calibrated periodically during the experiment. These transducers were used to measure the difference in static pressure across the slug (typically 10 to 40 kPa).

Air admission was measured with a calibrated Pitot tube mounted in a 1.5 m, 38 mm ID pipe fitted to the air inlet of the air injector. The water flow rate from the wash vat to the milkline was measured with a paddle-wheel flow meter mounted in the water supply line. This line was fitted with a ball check valve at the wash vat to prevent backflow and to ensure that the line was always completely flooded. A second paddle-wheel was mounted with it's axis of rotation flush with the bottom of the movable test section to measure the velocity of the bottom liquid layer in the milkline. All sensor signals were read by a 20 channel computer data acquisition board (Kiethly DAS 20 w/ EXP-GP). A sampling rate of 1000 Hz was used for fill depths and slug velocity. The pressure transducers and the flow sensors were sampled at 10 Hz.

Tests were performed with the movable test section (containing the fill depth sensors, paddle wheel velocity sensor and vacuum transducer) mounted at various locations in the milkline flow circuit. One test consisted of dynamic measurements during three complete air injection cycles of the air admission at the air injector, water intake from the wash vat, and vacuum levels at the various locations in the milkline as well as the slug velocity and length at the movable test section. These measurements were taken after about 10 air injection cycles to allow the flow characteristics to stabilize.

RESULTS AND DISCUSSION

Air injector timing: If the injector open time was not sufficient to allow the slug to travel through the entire milkline, as is the case in many existing milking systems, the slug broke and continued to and travel as an elongated wave which did not fill the milkline cross section. When the air injector was reopened this wave sometimes reformed as a slug but left a portion of the top of the milkline with no slug contact. In these experiments the injector open time was adjusted so that the slug formed at the beginning of the flow circuit had sufficient time to travel the complete pipe circuit. This was the only method found to assure contact of the slug with all surfaces of the milkline.

The volume of water drawn into the system during each cycle could be precisely controlled by changing the injector close time. This initial water volume determined the initial slug size. If the injector close time and corresponding initial slug size was too short the slug dissipated before reaching the receiver leaving part of the milkline with no slug contact. If the injector open time was too long the slug reaching the receiver was too large and flooded the receiver and sanitary trap. In these experiments the injector close time was adjusted so that the slug reaching the receiver has volume approximately equal to 1/3 of the receiver volume. This allowed for adequate cleaning of the receiver without flooding the sanitary trap.

In practice, the required injector open time will depend on the slug velocity (which can be controlled by the air admission rate) and length of the milkline. The injector close time will depend upon the length of milkline (which determines the required initial slug length), decay rate of the slug, and the rate at which water is drawn into the system.

Bottom liquid layer fill and velocity: Measurements of the depth of the liquid layer immediately ahead of the slug are presented in Figure 2. The liquid layer drains toward receiver during the air injector close time resulting in little or no liquid at the high point of the milkline. The liquid layer in the outgoing leg drains toward the closed wash valve resulting in an increased liquid layer near the beginning of the slug travel path. Liquid was also added to the milkline near the wash valve during the injector close phase further increasing the depth of the liquid layer at this point. The flow of liquid in the return leg is unobstructed and drains into the receiver resulting in slightly increased depth near the receiver.

The velocity of the liquid layer ahead of the slugs ranged from 0.5 to 1 m/s traveling in the same direction as the slug. As the slug passed, the liquid layer was rapidly accelerated to the slug speed. This is an indication that the slug is a region of intense liquid mixing. There is a long 'tail' in which the liquid being shed from the slug decelerates and stratified flow redeveloped.

Slug length and growth rate: Slugs always formed immediately upon opening the air injector. The slugs then grew to a length greater than could be accounted for by the liquid drawn into the system (Figure 3). After reaching a relative maximum in the early stage of travel the slug length decreased for the rest of its travel. The growth rate of slug was positively correlated with the fill fraction of the pipe ahead of the slug;

$$\frac{\Delta L_s}{\Delta x} = -0.23 + 1.1 a_f \tag{1}$$

(n = 54, $R^2 = 0.39$)

Where:

ΔL_s = Change in slug length between two measurement points (m)

Δx = distance between measurement points (m)

a_f = Area fraction of pipe filled with liquid ahead of the slug

The slugs grew when the depth of the liquid layer ahead of the slug was more than about 20 % of the pipe cross section and shrunk when liquid layer was less than this. The decrease in slug length was most rapid near the high point of the milkline where the depth of the liquid layer ahead of the slug was at it's minimum.

Slug velocity: The slug velocity measurements are illustrated in Figure 4. The slug had zero initial velocity and accelerated rapidly in the first few meters of milkline when the air injector is opened. The velocity then slowly increased or decreased, depending on system parameters. This driving pressure across the slug is balanced against resisting frictional, gravity and momentum forces. As the slug shrinks the resisting frictional and momentum forces are reduced. If the resisting forces decrease faster than the driving forces the slug accelerates. At the highest air flow rate in the 73 mm pipe the slug shrinks and accelerates rapidly in the return leg of the milkline.

Air-to-liquid velocity ratio: The ratio of air-to-liquid velocities, referred to as the holdup or slip ratio, is a parameter commonly use to describe two phase flows. Holdup ratios were calculated as follows:

$$H_a = \frac{v_a}{v_s} \tag{1}$$

$$H_s = \frac{v_a^s}{v_s} \tag{2}$$

Where :

H^a = Holdup ratio based on actual air velocity

H^s = Holdup ratio based on superficial air velocity

v_a = Air velocity taken as the volumetric air flow rate divided by the cross sectional area of milkline ahead of the slug filled with air (m/s)

v_a^s = Superficial air velocity, volumetric air flow rate divided by the cross sectional area of milkline (m/s)

v_s = Slug velocity (m/s)

The holdup ratio based on superficial air velocity (H_s) is useful for predictive methods as knowledge of fill depth is not required. This ratio was regressed against the pressure difference across the slug, slug velocity and slug length for all data for all three pipe diameters. The coefficients for the pressure difference and slug length terms were significant at the 95% confidence level.

$$H_s = 0.94 + 1.8(10) - 5\Delta P_s - 0.051 L_s \qquad \textbf{(3)}$$

(R ^{2} = 0.59, n = 86)

Where :

ΔP_s = Pressure difference across slug (Pa)

L_s = Slug Length (m)

The holdup ratio based on actual air velocity is useful as it gives an indication of the void ratio in the slug. This ratio was regressed against the pressure difference across the slug, slug velocity and slug length for all data for all three pipe diameters. The coefficients for the pressure difference and slug length terms were significant at the 95% confidence level.

$$H_a = 1.07 + 0.018\Delta P_s - 0.020 L_s \qquad \textbf{(4)}$$

(R ^{2} = 0.42, n = 86)

Increased pressure difference across the slug and reduced slug length increased the slip of air past the slug. The inverse of the holdup ratio was used to estimate the slug void ratio (volume of air in the slug / total air and water volume in the slug). The estimated slug void ratio ranged from 0.5 to 1 with most values falling between 0.7 and 0.8. These values correspond with estimates made from high speed photographs of the slugs and the range of values reported in Govier and Aziz (1972).

Wall shear stress : The forces acting on the slug can be calculated by integration of the momentum equation over a single liquid slug for one dimensional flow:

$$\rho_l \varepsilon_s A_p L_s \frac{dv_s}{dt} = A_p \Delta P_s - \rho_l \varepsilon_s A_p L_s f \frac{v_s^2}{2D} - \rho_l \varepsilon_s A_p L_s g \sin\theta - \frac{\rho_l A_f (v_s - v_l)^2}{2} \qquad \textbf{(5)}$$

Where:

ρ_l = liquid density (kg/m^3)

ε_s = liquid fraction of slug (1-void ratio)

A_p = pipe cross sectional area (m^3)

t = time (s)

A_f = cross sectional area of pipe occupied by liquid layer ahead of slug (m^3)

f = friction factor

D = pipe diameter (m)

g = gravitational acceleration (m/s^2)

θ = angle of pipe inclination (positive or negative depending on location of slug)

v_l = velocity of liquid layer ahead of slug (m/s)

The term on the left side of (6) is the force required to accelerate the liquid in the body of the slug. The terms on the right side of (6) are the pressure difference across the slug, frictional resistance between the slug and pipe wall, gravitational force due to pipe incline or decline, and the impact force of the slug on the slow moving liquid layer respectively.

In the middle portion of the milkline slug acceleration can be neglected as slug velocity is stable. The friction factor was calculated, neglecting slug acceleration, using measurements away from the ends of the milkline, of the pressure difference across the slug, area of the liquid film ahead of the slug, and the inverse of the holdup as an estimate of slug density. The calculated values of the friction factor fell between 0.008 and 0.016 and decreased with increasing value of the slug Reynolds number over the range of slug Reynolds numbers from $4 x 10^5$ to $1 x 10^6$. The magnitude of the friction factor and trend with Reynolds number agreed well with predictions from the Moody diagram for smooth walled pipe (f = 0.01 - 0.014). The useful mechanical force for cleaning is wall shear stress developed between the slug and the pipe wall and is calculated as follows:

$$\tau_w = \frac{f \rho_l \varepsilon_s v_s^2}{8} = \frac{\Delta P_f D}{4 L_s} \qquad \textbf{(6)}$$

Where:

τ_w = pipe wall shear stress (Pa)

ΔP_f = Pressure difference across slug due to friction (Pa)

The milkline wall shear stresses were calculated using (7) and measured values of slug length and the pressure difference across the slug due to friction based on the total pressure difference across the slug corrected for acceleration and gravity using (6), (Figure 5). These are average shear stress around the milkline cross section (i.e. top to bottom).

As the superficial sir velocity (air flow rate) was increased the wall shear stress averaged over the entire pipe length first increased and then decreased and the variation of shear stress along the milkline increased. Excessive air admission increased the slip coefficient (ratio of air to slug velocity) and amount of air entrained in the slug. Increased air in the slug reduces the slug density and shear stress it is capable of developing and also acts to break down the slug. Slug velocities of 7 to 10 m/s maximized the wall shear stress developed while minimizing the variation of shear stress along the pipe. The Nordic recommendations fall within this range (NDA, 1988).

SUMMARY AND CONCLUSIONS

The desired condition for cleaning is to contact all milkline surfaces with the slug of liquid at adequate velocity to provide mechanical cleaning action. If the slug breaks before reaching the receiver, due to insufficient initial slug size, insufficient air injector open time or excessive air admission, portions of the milkline surface will not come into contact with cleaning solutions. Excessive slug size causes flooding of the sanitary trap and is undesirable as this stops the cleaning process. When one slug is formed at the beginning of the milkline and maintained through the entire system, all surfaces will be have contact with the slug. In order to achieve this the air injector must be left open long enough for the slug formed at the air injector to travel the entire milkline. The initial slug length must be also sufficient and air injection rates limited so that the slug will not dissipate before it reaches the receiver.

The slug acts in some respects like a wave as it moves through the milkline. It picks up liquid at its face and loses liquid at its tail as it travels. The rate of liquid pickup increases with increasing fill depth in the milkline ahead of the slug. If the standing liquid layer in the milkline is not of sufficient depth the slug length decreases as liquid is shed at the tail faster than it accumulates at the face. The slug will then decrease in length until finally it dissipates. This process occurs during the first several air admission cycles as the liquid layer is forming.

Increasing slug velocity and density increase the mechanical cleaning action or shear stress at the pipe wall. The slug is an imperfect piston resisting the pressure differences across it. As the rate of air admission is increased the pressure difference across the slug is increased, the slip of the air past the liquid increases, and slug density decreases. Increasing the air admission rate and pressure difference across the slug does not produce a proportional increase in slug velocity and may decrease the shear force developed due to decreased slug density.

Optimal mechanical cleaning action is produced by slug velocities of 7 to 10 m/s. The rate of air admission through the air injector should be controlled to produce superficial air velocity of 8 to 12 m/s to achieve these slug velocities. Air admission rates above this maximum will result in reduced slug density and reduced mechanical cleaning action in the milkline.

REFERENCES

Agriculture Canada, 1990. Guidelines for the Installation and Operation of Milking and Milk Handling Equipment. National Liaison Group on Milk Quality,. 37 pp.

BSI, 1988. Milking machine Installations: Part 2. Specification of construction and Performance (BS5545:Part 2). British Standards Institution.

Govier G.W., and K Aziz, 1972. The Flow of Complex Mixtures in Pipes. Van Nostrand Reinhold Company, New York, 792 pp.

Grasshoff, A. and D.J. Reinemann, 1993. Zur Reinigung der Milchsammelleitung mit Hilfe einer 2-Phasen-Ströemung, Kieler Milchwirtschaftliche Forschungsberichte, Volume 45 pp 205-234.

Hetsroni, G., 1982. Handbook of Multiphase Systems. Hemisphere Publishing Corp., New York.

IAMFES, 1990. 3-A Accepted Practices for the design, fabrication and installation of milk handling equipment (3-A 606-03). International Association of Milk, Food and Environmental Sanitarians, United States Public Health Service, The Dairy Industry Committee.

ISO, 1983. Milking machine installations - construction and performance, ISO 5707. International Standards Organization.

MMMC, 1993. Maximizing the Milk Harvest: A Guide for Milking Systems and Procedures. Milking Machine Manufacturers Council of the Equipment Manufacturers Institute, Chicago, Il, 51 pp.

NDA, 1988. Nordic recommendations for milking machine plants: function, dimensions and installation. Nordic Dairy Associations' Committee Concerning Milking, The milk Hygiene Department, Arhus, Denmark.

Tragardh, C., and I. Von Bockelmann, 1980. Mechanical cleaning effect and pressure drop of air-water flow in horizontal glass tubes (vacuum dairy pipelines), Journal of Food Process Engineering, Vol. 3, pp 77-90.

Reinemann, D.J. and J. Book, 1994. Airflow requirements, design parameters and troubleshooting for cleaning milking systems. Proc. ASAE/NMC International Dairy Housing Conference, 31 January - 4 February, 1994, Orlando, Florida, USA.

Wallis, G.B., 1969. One Dimensional Two-phase Flow. McGraw Hill, New York, 408 p.

FIGURES

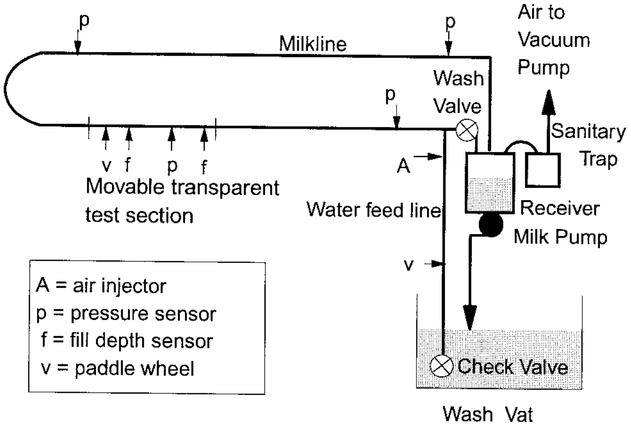

Figure 1–Experimental system diagram.

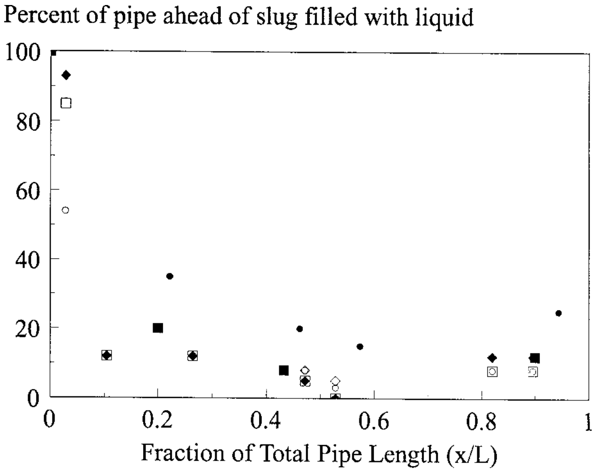

Figure 2. Percent of pipe ahead of the slug filled with liquid, (for all figures, D = internal pipe diameter, mm and v = superficial air velocity (m/s). (■ D = 98, v_a^s = 5.5; ♦ D = 73, v_a^s = 6.7; • D = 48, v_a^s = 9.1; □ D = 73, v_a^s = 12; ◊ D = 73, v_a^s = 18; ❍ D = 73, v_a^s = 20) .

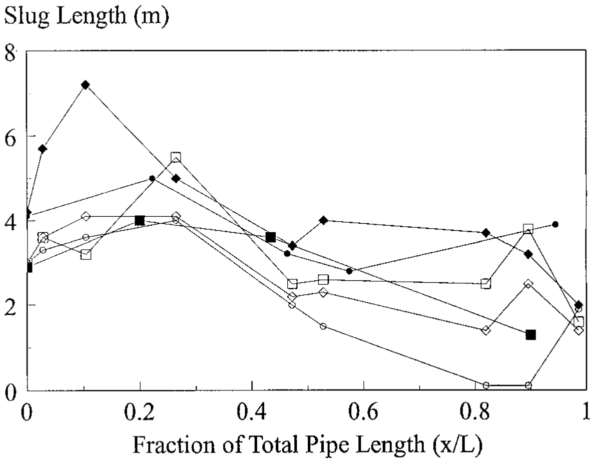

Figure 3. Slug length versus travel distance (■ D = 98, v_a^s = 5.5; ♦ D = 73, v_a^s = 6.7; • D = 48, v_a^s = 9.1; □ D = 73, v_a^s = 12; ◊ D = 73, v_a^s = 18; ❍ D = 73, v_a^s = 20) .

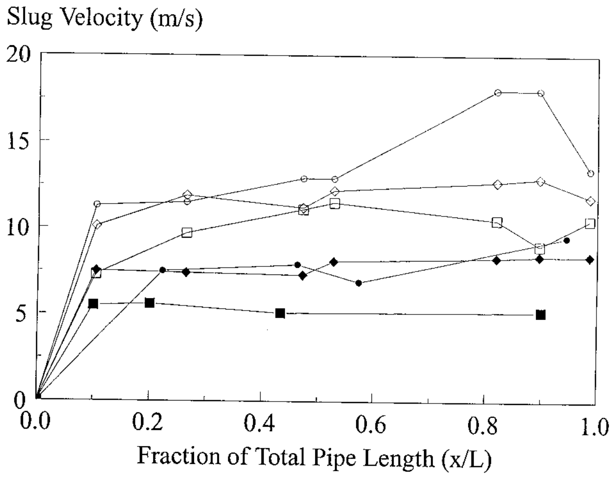

Figure 4. Slug velocity versus travel distance (■ D = 98, v_a^s = 5.5; ♦ D = 73, v_a^s = 6.7; • D = 48, v_a^s = 9.1; □ D = 73, v_a^s = 12; ◊ D = 73, v_a^s = 18; ❍ D = 73, v_a^s =20) .

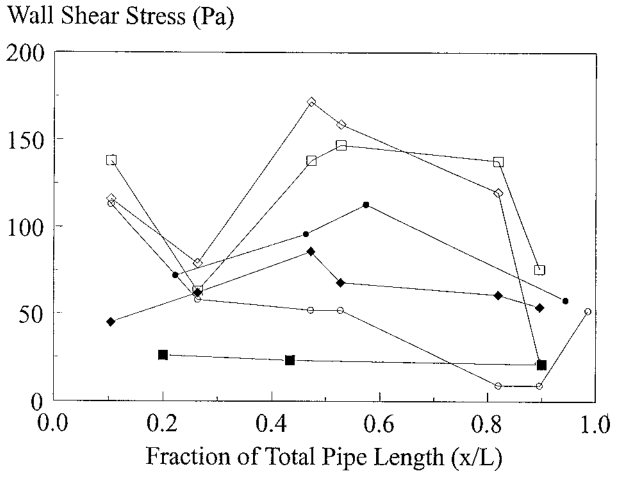

Figure 5. Average wall shear stress versus travel distance (■ D = 98, v^s_a = 5.5; ♦ D = 73, v^s_a = 6.7; • D = 48, v^s_a = 9.1; □ D = 73, v^s_a = 12; ◊ D = 73, v^s_a = 18; ❍ D = 73, v^s_a = 20) .