Significance of Two-phase flow in Piping System

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Wikipedia definition – "In fluid mechanics, two-phase flow occurs in a system containing gas and liquid with a meniscus separating the two phases."

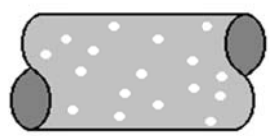
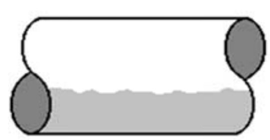
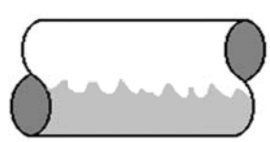
Two-phase flow is simultaneous flow of gas and liquid. Such flow is frequently found in heat exchange equipment. Two-phase flow can be termed as multiphase flow also. Water at saturation conditions exists as both a liquid and a vapor.

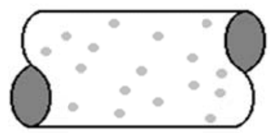
Two-phase flow is usually experienced in plants, where boiler produces vapor / steam. Pressurized water-filled tubes while heated through furnace, steam are generated.

In a piping system, at certain locations (viz. long horizontal / inclined run of pipe with relatively shorter riser / down comer), fluid flow can be such that there exists combination of liquid and vapor (gas) flowing. It can be condensate and steam.

Behavior of two-phase fluid flow is different from single-phase fluid flow. Simple relationships used for analyzing single-phase flow do not apply for analyzing two-phase flow. **Example:** The two-phase flow head loss can be many times greater than that of single-phase flow.

Various types of two-phase flow regimes can exist at different conditions. Few of them are depicted herein for reference.

Bubble Flow	
Plug Flow	
Stratified Flow	
Wavy Flow	

Slug Flow	
Annular Flow	
Spray Flow	

The most common two-phase flow regime is called slug flow, in which pipe cross section is filled alternatively with gas and liquid. Slug flow belongs to a class of intermittent flow that has very distinctive features and it occurs under special circumstances of two-phase gas-liquid flow.

Slug flow is an unsteady phenomenon with combination of stratified flow with separated flow (single-phase gas or vapor) i.e. moving liquid-bubble mass is being pushed by gaseous mass. When these two states act in random-like manner, unstable flow starts occurring in the form of oscillations and / or flow reversals, inducing pressure and velocity fluctuations, resulting in undesirable mechanical vibration of components in piping system. Thus, slug flow constitutes the most serious implication in two-phase flow.

In slug flow, velocity of gas or vapor portion is approximately 2 to 2.25 times of that of liquid portion. In slug flow regime, generally liquid rich slugs occupy the entire straight run of pipe and it travels at a speed that is a substantial fraction (half or slightly less) of the gas velocity and it occurs intermittently. This causes large pressure and liquid flow rate fluctuations and it looks like a large flow surge or a large wave. The length to diameter ratio of slugs varies with flow rates, pipe diameter and fluid properties.

Prior analyzing further, recapitulation on Froude Number is required.

Froude Number is a dimensionless number, defined as the ratio of inertia force on a fluid element to the weight of the fluid element i.e. the inertial force divided by the gravitational force. Froude Number can be expressed as:

$Fr = v / (g\ L)^{1/2}$

Where,
v = Velocity of the fluid element in m/s;
g = Acceleration due to gravity = 9.81 m/s^2;
L = Characteristic length / height / depth in m;

Froude Number has significance in fluid dynamic problems, where fluid weight plays an important role. It is proven that the slug characteristics are strongly influenced by Froude number in the liquid film, ahead of the slug.

Fr < 1 signifies a subcritical flow. For Fr > 1, the flow is characterized as supercritical flow. Fr ≈ 1 denotes a critical flow.

The mixing length of slug is a function of slug velocity. It has been derived that the mixing length increases with increasing slug velocities. Assimilation of the liquid film into the slug occurs in the mixing zone. The length of the mixing zone is determined by the mixing of gas and liquid and not the liquid alone.

The mixing length of slug can be expressed as an empirical function of the film Froude number. And, the mixing length has direct dependence on the film Froude number. The dependence is given by:

$L_m = M * Fr + C$

Where,
L_m = Length of the mixing zone in m;
M & C = Linear regression coefficients with units as [L];
Fr = Film Froude Number is a dimensionless number;

Through experiment, it is found that M = 0.13 & C = (-) 0.31.

Froude Number, Fr	0.5	0.8	1	1.25	2.5	4	8	10
L_m in m	-0.25	-0.21	-0.18	-0.15	0.02	0.21	0.73	0.99
Inference	**No Slug Flow**	**No Slug Flow**	**No Slug Flow**	**No Slug Flow**	**Slug Flow Starts**	**Slug Flow**	**Slug Flow**	**Slug Flow**

Slug flow ceases to be uniform, as the process of slug formation is random. Therefore, it is difficult to predict slug forces accurately. Characterization of slug flow pattern is mostly carried out by flow visualization method. Further reading of research articles is recommended.

In a piping system, slug forces are generated when the slug encounters change in flow direction. And, it generally occurs at elbows and tees. Slug force occurs due to change in momentum. The amplitude of the slug force for a 90 degree elbow is expressed as:

Slug force = ρAV^2 [Unit: Newton (N)]

Where,

ρ = Density of slug i.e. liquid-bubble mass in kg/m^3;

A = Internal area of cross-section of pipe in m^2;

V = Velocity of slug i.e. pushed by gaseous mass in m/s;

For an inclined pipe or riser, if gas flow can be cut off for substantial period until the accumulated liquid has been mobilized; dynamic piping load is generated from unsteady lumped mass traveling in the system. Such load has potential to heavily damage pipe supports, pipe bends and pipe tees.

Slug flow occurs mostly in piping networks transporting wet gas. Condensate collects gradually in horizontal segments of piping to form a plug and then the liquid plug undergoes hydraulic transport to the segments of piping where it is being "shot" with high velocity by overpressure. This is like a slug in a barrel of a gun. The slug then hits opposite bend in piping and it generates heavy blow loads on piping.

For piping systems, having tendency of having possible slug flow, all changes of pipe run direction shall require adequate restraints, to arrest sudden pressure thrust and associated dynamic load due to slug flow. Based on historical data, it is seen that standard guides and anchors (or line stops) are found to be inadequate to restrain slug flow. In many cases, special design of pipe supports is required. For slug flow, special design of pipe supports mainly offer adequate resistance to horizontal "shot" loads.

This slug load, as calculated is ideally suited for time-history analysis, to study the movement of liquid lumped mass w.r.t. time and its impact on elbows and tees. Today's pipe stress analysis software (viz. CAESAR II, AutoPIPE) has features to carry out such analysis. Thus, it has become easier to predict the slug flow, to calculate slug frequency, to work out dynamic forces acting on piping components over time. In turn, it helps to appraise preventive measures to avoid slug flow or to diminish its effects.

In a piping system, slug flow problems can be overcome with slug catchers (which collect the slugs) or by developing a pipe system that has provisions to break the slugs along the piping length.

For a steady state gas and liquid flow, the "average" flow rate of liquid can be adequately handled with a small knockout pot. However, in slug flow, due to variation in pressures and flow rates, large slug catcher is required to catch big liquid slugs with relatively short slug arrival time.

References:

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4. Ivor R. Ellul, Geir Saether, Mack E. Sheppen, "The Modelling of Multiphase Systems under Steady-State and Transient Conditions - A Tutorial", Pipeline Simulation Interest Group

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