Analysis of Pressure and Flow Transients in Systems with Heat Additions

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The occurrence of pressure and flow fluctuations in fluid flow systems with heat addition has been noted in many isolated instances. Under certain conditions of local boiling, which includes a boiling-like mechanism at super-critical pressures, intense sounds and mechanical vibrations can be generated. A mechanism for these fluctuations is derived based on fundamental considerations. A large change in density with enthalpy, such as occurs at a liquid to vapor phase change point or in the super-critical region, will introduce a flow transient. Changes in the frictional resistance to flow can also initiate a transient condition.

Introduction

Interest in utilizing convective regenerative heating of liquid rocket fuels has focused attention on this type of heat-transfer. For several of the hydrocarbon fuels such as RP-1 and para-hydrogen, this involves heat-transfer in the region of the thermodynamic critical temperature at critical and supercritical pressures. Reports of several investigations to determine heat-transfer coefficients in this region contain references to severe pressure and flow oscillations under certain operating conditions. Attempts to explain these phenomena have not been successful to date. In this paper is proposed the mechanism for the pressure and flow oscillations based on a one-dimensional model of the diabatic flow system.

Two cases where heat transfer to fluids in the thermodynamic critical region is encountered are: the operation of a fluid flow system, particularly a natural-circulation system near the critical point, is desirable because of the large heat capacity and large density gradients that exist in this region; and, the fluid passes through the critical region as it is being heated in a super-critical pressure system. An example of the second case is the convective regenerative heating of liquid propellants at the rocket nozzle such as the RP-1 fuel mixture or hydrogen.

The occurrence of pressure fluctuations severe enough to induce mechanical vibration of the tube and subsequent rupture has been reported in several papers. Hines and Wolf in a study of the pressure fluctuations encountered in a diabatic flow of RP-1 and Diethylcyclohexane (DECH) at supercritical pressures reported fluctuations in pressure of 380 psi peak to peak with frequencies in the range from 1000 to 10,000 cps. The vibration was very destructive to thin-walled tubing. In tests with thick-walled tubing, similar pressure fluctuations were measured but the tubes were able to resist the effect of the mechanical stresses. Their paper mentions several similar occurrences reported in the literature.
In a documentation of boiling songs and associated mechanical vibrations of water systems with heat addition, Firstenberg reported the results of informal interviews with various researchers in which boiling songs, mechanical vibrations, and pressure fluctuations were discussed. Several of the conclusions reached were:

1. Under certain conditions of local boiling, which includes a boiling-like mechanism at supercritical pressures, intense sounds (boiling songs) and mechanical vibrations can be generated.
2. The occurrence of these intense sounds and mechanical vibrations are intimately related to the operating conditions in the heater.
3. The boiling songs and associated vibrations are accompanied by large-amplitude pressure and flow fluctuations, although such fluctuations may occur without the generation of sounds or vibrations.
4. The occurrence of boiling songs and associated vibrations appears to be confined to local (subcooled) boiling systems. There has not been a recorded occurrence of these phenomena in bulk boiling (net vapor generation) systems.
5. The unusual phenomena result from pressure waves and/or flow fluctuations which induce variable heat transfer in the system. The variability in the heat-transfer rate and energy dissipation of the pressure wave results in the intense sounds and vibrations.

In the summary it was concluded that the severity of the vibrations and intensity of the sounds indicate a possible limiting condition for some boiling systems. Because of other more immediate needs in cases where these phenomena were observed, they were considered to constitute a nuisance condition, and thus, were not investigated systematically. It was recommended that some systematic investigation of these phenomena be initiated, directed at obtaining an understanding of the cause and effect relations, and discovering methods for eliminating the occurrences.

Goldman in a report of heat-transfer experiments to supercritical water at 5000 psia distinguished between heat transfer without "whistle" or a "normal" mode and heat transfer with "whistle". The frequency of the whistle sound varied from about 1400 cps to 2200 cps. Inlet temperature appeared to have the greatest effect on frequency. Pressure had little, if any, effect on the frequency. A system pressure increase of about 50 psi occurred at the onset of the whistle sound.

Morgan and Brody discuss the term "geysering" as applied to missile applications. The term "geysering" is applied to the specific phenomenon that occurs in a liquid system when a column of liquid in long vertical lines is expelled by the release of vapor at a rate in excess of that rate which may occur as a normal function of bubble release. This is also known as slug flow or the "coffee percolator" effect.

The result is an expulsion of liquid from the vertical line. Refilling the line by gravity action from a storage tank above the results in a pressure surge analogous to water hammer. The pressure surges so produced can be very large and damage to feed lines, valve supports, and line supports as result of geysering is a common occurrence.

An effective solution to this problem was to run two lines from the liquid tank to the engine with an interconnecting line at the lower end. When one of the lines is insulated, a cold leg results and a natural-circulation is established. The resulting flow was sufficient to prevent the heat input in the uninsulated leg from vaporizing the fluid.

Flow and pressure oscillations in a liquid-oxygen system of the Saturn Booster rocket have been reported by Platt and Wood. The oscillations occurred in the
initial startup of an evaporator designed to supply gaseous oxygen to the fuel tank for pressurization by evaporating liquid oxygen. Pressure oscillated by as much as ±300 psi at a frequency of 1/3 cps with the flow stopping in the worst cases. Amplitude diminished with time to ±50 psi in the first 30 to 60 sec of the test run.

The occurrence of pressure and flow fluctuations in the cool-down of a cryogenic system is discussed by Bronson, et al. Cool-down time was defined as the time interval between introduction of liquid hydrogen into a warm cryogenic system and the appearance of a continuous flow of liquid at the discharge end of the system. During experiments to measure the cool-down time, the pressure was found to undergo periodic fluctuations with a variable frequency. A model was presented to calculate the frequency of the pressure fluctuations.

In the first test run of a KIWI-B1 reactor at power with liquid-hydrogen propellant, severe hydrogen pressure fluctuations were observed at the pump outlet early in the startup cycle. It was believed that these fluctuations resulted from an unchilled by-pass line at the pump outlet.

Lewis, Goodykoontz, and Kline in a study of boiling heat transfer to liquid hydrogen report that under some operating conditions fluctuations of pressure and flow become uncontrolled.

This paper presents a hypothesis on the nature of the driving mechanism of the pressure and flow oscillations based on deductions from the conservation equations and the equation of state. It will be shown that the relationship of thermodynamic properties in the critical region or at a phase change point are very conducive to flow and pressure oscillations. The analysis is valid for either forced or natural-circulation flow. Plots of the similar thermodynamic characteristics of water and Freon-114 are presented.

Analysis

The flow system to be considered consists of a constant area tube through which a fluid is flowing either by forced or natural-circulation. A one-dimensional approximation is made. Laws of conservation of mass, momentum, and energy are written which describe the fluid flow through such a tube. The density is evaluated as a function of enthalpy alone at some reference pressure. Two expressions are obtained which describe the mass velocity in this system. One expression describes the local change in mass velocity as a function of the heat input and thermodynamic condition of the fluid. The second expression describes the time variation of the mass velocity produced by the interaction of the pressure drop with the local change in mass velocity. It is shown that the thermodynamic condition of the fluid conducive to large local changes in mass velocity with heat addition are those encountered when the fluid is in certain portions of the supercritical region or at a liquid to vapor phase change point.

The conservation equations for this system can be written

\[ \frac{\partial p}{\partial t} + \frac{\partial G}{\partial z} = 0 \]  

(1)

\[ \left( \frac{\partial G}{\partial t} \right) + \frac{\partial}{\partial z} \left( \frac{G^2}{\rho} \right) = -\frac{\partial p}{\partial z} - \frac{fG}{2dp} - \rho g, \]  

(2)
An equation of state of the form

\[ \rho = \rho(h, p^*) \]  

is used. This Equation states that the density can be evaluated as a function of enthalpy alone at some reference pressure and its validity depends on the major effect of heat transfer being a change in enthalpy. This simplifies the analysis considerably without eliminating the basic driving mechanism of the flow oscillation and pressure fluctuations.

Neglecting the effects on enthalpy rise rates of dissipation and pressure changes with space and time, Eq. (3) can be written

\[ \rho(\partial h/\partial t) + G(\partial h/\partial z) = Q/A \]  

In the equation of state density is not a function of pressure, hence, this model does not permit compression with increases in local pressure. This means that local pressure and velocity disturbances are propagated at the speed of sound evaluated at the reference pressure of the fluid. A physical model is a string of beads moving along at some uniform velocity. If suddenly one of these beads expands to twice its linear length, all of the beads are accelerated along the length of the string. The momentum equation must therefore be integrated over the entire tube length and is used to represent the behavior of the average mass velocity, \( G \), only:

\[ (dG/dt) = (1/L) (\Delta P - F) \]  

where

\[ \bar{G} = (1/L) \int_0^L G dz \]  

\[ \Delta P = \text{available driving pressure and the total resistance to fluid flow, } F, \text{ is given by} \]

\[ F = \left( \frac{G^2}{\rho} \right)_{\text{exit}} - \left( \frac{G^2}{\rho} \right)_{\text{inlet}} + \int_0^L \rho \frac{dG}{dz} dz + \int_0^L \rho g dz \]  

The mass velocity, \( G \), is a function of \( z \) and \( t \). Therefore, it is desirable to obtain explicit expressions for these relationships. Combining the equation of state and the continuity equation, Eq. (4) and (1), we obtain

\[ (\partial p/\partial t) = (dp/\partial h) (\partial h/\partial t) = - (\partial G/\partial z) \]  

Eliminating \( (\partial h/\partial t) \) in Eq. (5) and (9) gives

\[ (\partial G/\partial z) = (1/\rho) (dp/\partial h) \quad G(\partial h/\partial z) = Q/A \]  

The momentum equation, Eq. (6), is repeated here for continuity of thought in the succeeding discussions.
The simultaneous solution of Eqs. (10) and (11) would yield the average mass velocity in the fluid flow system as a function of time. It is possible, however, to obtain a quantitative picture of the flow behavior by examination of Eqs. (10) and (11).

Since the driving force for the flow and pressure oscillations in the system being considered is the heat input, we first examine Eq. (10). The term \( \frac{dp}{dh} \) will always be negative for the fluids of interest in this type of heat transfer. In addition the numerical magnitude \( \frac{dp}{dh} \) can be quite large under certain thermodynamic conditions to be discussed below. Thus we see that if the bracket term \( [G(\frac{dh}{dz}) - \frac{Q}{A}] \) is other than zero, there will be a local change in mass velocity which will interact with the momentum equation, Eq. (11), to give a time rate of change in the average mass velocity.

It is of interest to inquire under what conditions the bracket term will be positive, zero or negative. In steady state conditions the heat input is absorbed by the flowing fluid, hence \( [G(\frac{dh}{dz}) - \frac{Q}{A}] = 0 \). If a change in \( Q \) occurs, the equilibrium balance will be upset. If the heat capacity of the fluid undergoes a change, then \( \frac{dh}{dz} \) will change also. Hence we see the possibility of \( [G(\frac{dh}{dz}) - \frac{Q}{A}] \) being positive, negative, or zero and if this difference is multiplied by a large number, quite large positive and negative values of \( \frac{dG}{dz} \) can be obtained.

The momentum equation contains the damping terms which will determine the magnitude of the flow oscillations. With sufficient damping the flow oscillations could be suppressed but this is not a desirable operating condition.

In the thermodynamic critical region or at a liquid to vapor phase change point, the conditions favorable for the postulated oscillation mechanism are present. Scarcity of thermodynamic data in this region hamper extension to fluids other than those to be discussed. This, however, should point the way to the data that must be available for an analysis of flow instability.

One of the conditions necessary for large changes in \( \frac{dG}{dz} \) is a large \( \frac{dp}{dh} \). Plots of \( p \) vs \( h \) for Freon-114 and water are shown in Figures (1) and (2). As can be seen there is a relatively narrow range of enthalpies for which this condition will hold. Since a fluid being heated in this region would enter the heater section at an enthalpy below that for which \( \frac{dp}{dh} \) becomes large, passing into the range for which \( \frac{dp}{dh} \) is large, means that a fluid control volume experiences non-uniform accelerations. As the fluid enters the heater section, it experiences a uniform acceleration up to the point where \( \frac{dp}{dh} \) changes slope. It then experiences a greater acceleration which means an increase in \( G \) and a decrease in \( \frac{dh}{dz} \). If the \( G(\frac{dh}{dz}) \) product increases, then \( [G(\frac{dh}{dz}) - \frac{Q}{A}] \) changes in value resulting in a change in \( \frac{dG}{dz} \). If the damping in the momentum equation is not sufficiently large, there will be sustained flow oscillations as \( [G(\frac{dh}{dz}) - \frac{Q}{A}] \) changes its value and sign periodically.

Another condition which is encountered is the change in \( \frac{dh}{dz} \) which is due to a large change in heat capacity of the fluid in the critical region. This term can be determined from a measured temperature distribution between the inlet and outlet of the heater section as is shown below:

\[
\frac{dh}{dz} = (\frac{dh}{dT})p(\frac{dT}{dz})
\]
As \( C = (\partial h/\partial T) \) increases, \( (dT/dz) \) will decrease so that the true numerical magnitude trend of \( (\partial h/\partial z) \) may be in doubt. Generally an increase in \( G \) would result in a decrease in \( (\partial h/\partial z) \) but if the fluid is in the critical region, the decrease in \( (\partial h/\partial z) \) may be offset as conjectured previously. All that is necessary to precipitate an unstable condition is that the product of \( G(\partial h/\partial z) \) change.

**Conclusions**

It has been hypothesized, based on an examination of the basic conservation equations and the behavior of the thermodynamic properties of a fluid near its critical state or at a liquid to vapor phase change point, that the mechanism for the sustained pressure and flow oscillation is due to the fluid condition which can be defined in terms of a change in slope of \( dp/dh \). It is shown that the change in gradient of this slope is the primary mechanism for the oscillation. It is conjectured that heat addition to any fluid which exhibits this characteristic would result in flow oscillations provided that the sharp change in the \( (dp/dh) \) gradient occur somewhere in the heated section. Secondary mechanisms such as the change in heat capacity and heat transfer characteristics also enter the picture as shown in the combined state, energy, and continuity equation. The fact that viscosity is approaching or at a minimum concurrently with the primary mechanism provides decreased damping for the flow oscillations through the coupling with the momentum equation.

Further experimental work needs to be done to verify and refine this analysis. A heat-transfer loop presently being constructed at the University of Oklahoma will be used to check the preceding analysis. The oscillation threshold of the system with four different fluids is to be checked for agreement with the analysis.

**Nomenclature**

- **A** Cross sectional area for flow, ft\(^2\)
- **F** Total resistance to fluid flow -- composed of friction, elevation, and acceleration pressure loss, lbf/ft\(^2\)
- **f** Friction factor
- **G** Mass velocity, lbm/sec ft\(^2\)
- **\( \bar{G} \)** Average mass velocity in tube, lbm/sec ft\(^2\)
- **g** acceleration of gravity, ft/sec\(^2\)
- **h** Enthalpy, Btu/lbm
- **L** Tube length, ft.
- **p** Static pressure, psi
- **p^*\)** Reference pressure for fluid property evaluation
- **Q** Linear rate of heat input to fluid, Btu/(sec)(ft)
- **t** Time, sec.
- **z** Linear dimension, ft
- **ρ** Density, lbm/ft\(^3\)
References


Fig. 1. Isobars of Density-Enthalpy for Water
Fig. 2. Isobars of Density-Enthalpy for Freon-114 in the Critical Region