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A dynamic lumped parameter model of injection cooling system for liquid subcooling

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ABSTRACT

An injection cooling system for storage of a liquid has been studied theoretically. Cooling of the liquid is performed by passing a gas through the liquid; as the liquid evaporates into the gas phase, latent heat is transferred from the liquid resulting in liquid cooling. Among various storage methods, liquid subcooling by gas bubbling offers a simple but efficient solution, especially when short term liquid storage at low subcooled condition is needed at low cost. This type of cooling process is a case of simultaneous interphase heat and mass transfer. Heat exchange between the liquid and the surroundings also determines the overall efficacy of the process. Consideration of the two phase transport phenomena makes the theoretical analysis of this process very complex. However, for quick evaluation of the storage performance of such a system, a realistic but simplified model has been developed without involving the complex transport phenomena-based conservation equations. This model would also help in evolving a preliminary design of injection cooling system, as well as in assessing the effects of various operating and design parameters on the system performance. Such a model has been presented in this paper. Simulation runs were carried out and the model has been validated considering storage of liquid oxygen. Satisfactory match between the limited experimental data available in the literature with the model predictions has been found, thereby supporting the usability of the model for the said purpose.

1. Introduction

Liquid subcooling for long duration storage of liquid in several fields like space exploration, medical and bio-medical applications, chemical and pharmaceutical industries, LNG transport, food processing and storage are being carried out extensively, to reduce the evaporative loss of the liquid due to heat in-leak from the ambient. One of the ways of achieving subcooling is by injecting a non-condensable and insoluble gas through the liquid [1–6]. Such an effect was first reported by Minkoff et al. [7], who observed different degrees of boiling suppression in different cryogenic liquids (nitrogen, oxygen, air, argon) on bubbling different gases like helium, hydrogen, argon, oxygen, air and neon through the liquids. This method proves to be effective, comparatively cheaper and operationally simpler than other cooling or refrigeration methods, and hence is found to be useful in situations where high degree of subcooling is not required.

A typical injection bubbling system is shown in Fig. 1. A gas is bubbled through a liquid using a gas sparger. The gas should be insoluble or sparingly soluble to retain its identity, and also to eliminate any possibility of the release of heat of dissolution. A difference between the saturation pressure of the liquid and partial pressure of the liquid component inside the gas bubble makes the liquid evaporate into the gas bubble. The thermal interactions between the gas bubble and the liquid are shown in Fig. 2; latent heat transfer from the liquid to the gas during liquid evaporation tends to cool down the liquid while warming up the bubbles. This coupled heat and mass transfer could result in a temperature difference between the liquid and gas thereby triggering an interphase sensible heat transfer. Any interphase heat and mass transfer are profoundly affected by the two phase fluid dynamic interactions due to evolution of different types flow regimes. In case of bubbly flow, dispersion, coalescence, deformation, and breakup of the bubbles influence the heat and mass transfer. Thus the overall thermal performance of the injection cooling system gets dictated by several operating variables like gas flow rate and temperature, vessel pressure, vessel dimensions, sparger design and configuration etc., that typically affect any two phase system.

There are only a handful of research studies reported in the open literature. An analytical model for liquid cooling by gas bubbling was proposed by Yudaev et al. [3] and showed that the cooling of water is possible by bubbling air through it. Except this work, rest of the studies were carried out with cryogenic liquids like liquid oxygen, liquid hydrogen, liquid nitrogen etc. Larsen et al. [1] studied the subcooling of

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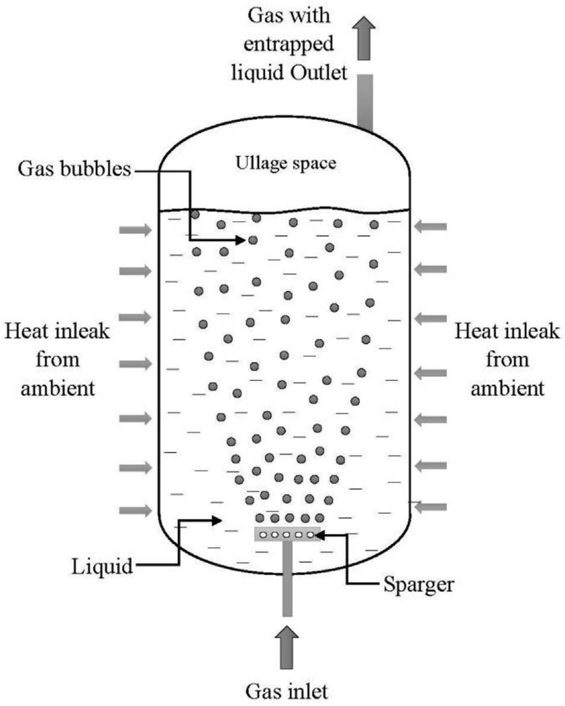

Fig. 1. Schematic of bubbling system for liquid subcooling.

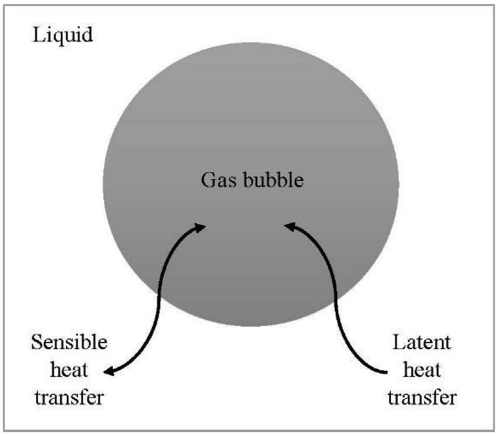

Fig. 2. Mechanism of injection cooling showing simultaneous heat and mass exchange between liquid and gas bubble.

liquid oxygen (LOX) by helium and nitrogen bubbling, both analytically and experimentally, in order to prevent the boil-off loss of LOX in the suction line of H-1 engine booster used in Saturn rocket. Considerable amount of subcooling was obtained, which was sufficient to reduce the boil-off loss of LOX. Schmidt [2] performed experiments on liquid hydrogen (LH2)-Helium (GHe) system to identify the feasibility of liquid subcooling by gas bubbling. Fair agreement between the experimental results and the analytical solution of Randolph and Vaniman [8] was obtained. Great importance was given on the design of cryogenic storage vessel in terms of the orientation and number bubbler ports. Theoretical model and experimental data on injection cooling were also reported by Cho et al. [4] and Jung et al. [5] with LOX-GHe system. Subcooling of LOX by injecting room temperature GHe was observed. Ramesh and Thyagarajan [6] performed experiment with LOX, LH2 and liquid nitrogen (LN2) by injecting GHe. They found the dependence of subcooling on gas injection temperature and gas flow rate. A numerical model in line with Cho et al. [4] was also presented by them.

Theoretical prediction and evaluation of the performance of injection bubbling system may be done by considering momentum, heat and mass transfer between liquid and gas (bubbles). Rigorous simulation helps in developing good understanding of the injection cooling phenomenon, but would involve solution of a coupled set of non-linear transport-phenomena equations. However, such detailed simulation is not necessary for design which needs quick but realistic performance prediction. A simplified model incorporating all the fundamental processes involved in the system will suffice for this purpose. In the present study a simplified but realistic approach has been adopted to quickly evaluate the system performance as well as to estimate the effects of various process parameters without detailed modeling of bubble dynamics. For the first time, bubble dynamic effect has been accounted for and incorporated in the modeling of this process. A numerical model has been developed, simulated and verified with the experimental results reported in the literature to justify the applicability of such a simplified model for assessing the cooling performance of injection cooling system. No design methodology for such systems is available in the literature. This study would enable one to know the operating range, and to evolve a preliminary design of an injection cooling system.

2. Modeling

In light of the earlier discussion, any model of injection cooling should include coupled heat and mass transfer between the gas bubble and the liquid. Bubble flow effect has been incorporated by considering bubble volume, bubble rise velocity, and residence time of the bubbles, which would enable accounting for the liquid-bubble interactions. A lumped parameter approach has been adopted for modeling whereby only one temperature has been assumed each for gas and liquid.

2.1. Bubbly flow model

2.1.1. Bubble formation at orifice

When a gas is sparged into the liquid through an orifice, bubble formation takes place at the orifice mouth. The bubbles start growing and, after reaching a critical volume, get detached from the orifice mouth and rise through the liquid. The bubble formation at the orifice mouth takes place in different ways like bubbling, chain bubbling, jetting and wobbling, depending on the orifice material and configuration, gas flow rate, properties of gas and liquid, and the gravitational force acting on the gas-liquid system. Several studies [9–13] have been carried out to determine the bubble size formed at a single orifice mouth. As proposed by Hughes et al. [9], the volume of a bubble at the time of detachment from a single submerged orifice can be found from Eq. (1), when the liquid is stagnant and the orifice is completely wetted.

$$V_b = 1.82\frac{\pi d_o \sigma}{g(\rho_l - \rho_g)} \tag{1}$$

In deriving Eq. (1), the bubble has been assumed to remain spherical throughout the formation process up to its deatchment from the orifice mouth.

The gas-liquid interfacial area is taken same as the surface area of a single spherical bubble, as given by Eq. (2).

$$A_b = 4\pi r_b^2 \tag{2}$$

The radius of the (spherical) bubble after detachment from the single submerged orifice can now be determined from Eq. (3).

$$r_b = \left(\frac{3V_b}{4\pi}\right)^{(1/3)} \tag{3}$$

The bubble gets detached from the orifice mouth when the sum of the inertial force and buoyancy force exceeds that of the surface tension force and the drag force. For constant and steady flow rate of gas, the bubble generation frequency remains constant, and can be determined