Numerical and Experimental Investigations of Liquid Subcooling by Gas Injection

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Abstract

Boil-off loss is a major concern in the long term storage of cryogenic liquids because they boil-off easily due to their low normal boiling point and low heat of vaporization. Several techniques such as Zero Boil-off (ZBO), insulated storage tanks, liquid subcooling etc., have been in use for the reduction or elimination of liquid boil-off. Injection cooling is used to reduce liquid boil-off. In this method, the liquid is kept subcooled (below its boiling point temperature at the tank pressure) by injecting a preferably non-condensable and insoluble gas through the liquid. Subcooling occurs due to liquid evaporation into the injected gas as well as into the ullage (the vapor space above the liquid).

The performance of an injection cooling system is analyzed by considering the two-phase hydrodynamics, and the interphase heat and mass transfer between (i) the liquid and the gas during the bubble rise through the liquid, and (ii) the liquid and ullage. There are only a few theoretical and experimental studies on the injection cooling system in the open literature. These studies attributed the liquid subcooling solely to the liquid evaporation into the injected gas bubbles, without including the effects of two-phase hydrodynamics. A review of the experimental data on injection cooling indicated that the liquid evaporation into the ullage, besides that into the injected gas, should have a significant effect on the liquid subcooling. Moreover, the effects of the type, configuration (diameter and number of holes), and submergence of the sparger, the initial liquid level, and vessel size and shape on the performance of an injection cooling system have not been addressed in the reported studies.

In view of the above, two types of modeling have been proposed in this thesis for the performance evaluation of an injection cooling system. First, a lumped parameter model of injection cooling system has been developed considering the combined effects of bubble dynamics, and interphase heat and mass transfer between liquid and gas bubbles. The bubble dynamic effects and the gas-liquid interfacial area for heat and mass transfer have been included by adopting the single bubble approach and gas holdup approach. In addition, the heat inleak into the system has been considered in these models. The effects of gas flow rate, gas injection temperature, tank dimensions (tank diameter and liquid height), and heat inleak on the cooling performance of an injection cooling system have been studied.

Next, we developed a modified lumped parameter model by considering the heat and mass transfer between liquid and bubbles, liquid and ullage. Also, heat transfer between the liquid below and liquid above the sparger, and heat inleak to the liquid as well as to the ullage have been considered. This modified model provides a more realistic theoretical visualization of injection cooling and helps in evaluating the effects of surface evaporation on the process performance. The effects of gas flow rate, gas injection temperature, heat inleak, ullage height, and sparger type and design (diameter and number of sparger holes) on the cooling performance of an injection cooling system have been evaluated using this model.

A design strategy of an injection cooling system has been presented, and experimental studies on injection cooling have been carried out using a water-air system. The experimental setup has been developed as per the design strategy. Experimental runs were made to determine the effects of gas flow rate and sparger hole diameter of ring sparger on the water subcooling on injecting air. Thus the applicability of an injection cooling system for the subcooling of non-cryogenic liquids has been evaluated. The experimental data have been used to validate the developed lumped parameter model.

From our work, we conclude that gas flow rate and gas injection temperature affect the performance of injection cooling significantly. The rate and extent of liquid subcooling increase with an increase in the gas flow rate. Maximum cooling is obtained when the gas is injected at the same temperature as the initial temperature of the liquid. An increase in gas injection temperature reduces the rate and extent of liquid cooling, and eventually results in liquid heating. The maximum permissible gas injection temperature that would provide liquid cooling depends on the gas flow rate, vessel dimension, and the type of gas-liquid system. The surface evaporation of the liquid into the ullage plays a significant role in dictating both the rate and the extent of liquid subcooling. The diameter of the sparger hole affects liquid cooling, while the number of sparger holes has a negligible effect on the cooling performance. Injection cooling should be applied when the liquid temperature approaches the boiling point temperature of the liquid at the tank pressure. Under a high degree of subcooling, liquid vapor pressure is low, so that the rate of evaporation and hence the cooling rate decrease. This fact has a significant bearing on the practical implementation of the injection cooling process, especially for the long term storage of a cryogenic liquid. Firstly, injection cooling may be applied intermittently (for example, it may be stopped if the liquid temperature is at or below a user-defined threshold (subcooled) liquid temperature), and secondly, the gas flow rate and temperature should be adjusted depending on the desired rate and extent of cooling to save material and energy cost.

Keywords: Injection cooling, Evaporative cooling, Surface evaporation, Gas-liquid heat and mass transfer, Space cryogenics, Cryogenic propellant, Two phase gas-liquid flow, Bubble column, Sparger, Lumped parameter model