INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 35 (2010) 12993–13003

Available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/he

Literature research on the production, loading, flow, and heat transfer of slush hydrogen

Young Moo Park

Dept. of Mechanical Engineering, Ajou University, Wonchon-dong san 5, Paldal-Gu, Suwon 442-749, Republic of Korea

ARTICLE INFO

Article history:
Received 24 December 2009
Accepted 13 April 2010
Available online 21 May 2010

Keywords:
Slush hydrogen
Cryogenic propellant
NASP
Freeze-thaw
Auger

ABSTRACT

This study summarizes the available information on slush hydrogen and answer pending engineering questions that arise in the design of slush hydrogen propellant systems. The four methods for the production of slush are discussed. For storage, slush hydrogen must be pressurized, free from impurities, and continuously upgraded. Slush flowing at low flow rates has a higher viscosity than the liquid, however at higher velocities it approaches the viscosity of neat liquid. For the entire range of natural convection and nucleate boiling, the heat transfer at the triple-point temperature and pressure is nearly the same for the liquid and slush. The natural convection from smooth surfaces for slush can be predicted using available correlations. However, for engineering analysis and design of a system involving a slush cryogenic propellant, reliable information is required on production, flow, heat transfer, and instrumentation of these fluids. Some relevant and important aspects of slush hydrogen which have not yet been fully answered are presented.

1. Introduction

Liquid hydrogen has a high specific impulse. Thus it has become an important fuel for rockets and was considered for use with the National Aero-Space Plane (NASP) in the U.S. and is considered for use with the reusable space shuttle in Japan. Some of the problems associated with its use as a propellant are its low density, short holding time due to low temperature, and unstable flight conditions caused by forces due to the sloshing of liquid in the tank. By slushing hydrogen, the density and heat capacity are increased, thus reducing the tank size requirements and increasing the holding time and/or reducing the insulation needed. For these, slush hydrogen has been considered as a fuel for reusable space shuttles, a coolant for cold neutron generation, as well as the transport and storage of hydrogen as a clean energy source.

Slush hydrogen is a two-phase solid–liquid mixture of cryogenic fluid and particles at the triple point of para-hydrogen ($P = 0.007042$ MPa, $T = 13.80$ K). This paper addresses the problems associated with production, storage, flow, and heat transfer of slush hydrogen and recommends further work be performed in these areas for proper engineering analysis of the systems involving the use of slush hydrogen cryogenic propellants.

Two advantages of slush hydrogen over liquid hydrogen are increased density and reduced fuel loss by evaporation. Due to these advantages, a substantial performance gain can be obtained. Adamson [1], reported that slush hydrogen could be used advantageously to increase payload and storage capabilities and to reduce or eliminate tank venting. For example, the payload of a Saturn V/S-IVB Lunar Logistics Vehicle can be increased by 40% by using 50% solid slush [2a,b]. To design a large scale system for production and utilization of slush hydrogen in the National Aero-Space Plane, which is reusable like a space shuttle, requires detailed knowledge of production, storage, loading and transfer, the effects of gas pressurization, and thermodynamic and transport properties of slush hydrogen. Dwyer and Cook [3], and

E-mail address: youngmoo@ajou.ac.kr
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2010.04.074

Roder [4], have reported the results for thermodynamic properties of liquid, solid, and slush hydrogen. Esgar [5], reviewed some of the research done in 1970 by NASA. Voth et al.[6] performed a study at the NBS in Boulder, Colorado, for the instrumentation used for slush hydrogen up to the mid-1980's. This study includes level sensors, density measurement, direct mass gaging at normal gravity, total mass gaging in zero gravity, and flow meters. Some other reports that discussed measurement techniques for liquid level determination or density determination are Knight et al.[7], Kocher and Brown [8], Weitzel et al.[9], Sindt and Ludtke [10], Daus and Schrawer [11], and NBS [12].

2. Production

Production includes all operations required to subcool liquid hydrogen to its triple-point and to produce the solid consistency required. There are several methods: (a) freeze-thaw, (b) auger, (c) nozzle expansion, and (d) helium injection. These are the only methods in the reviewed literature; however, methods other than these are possible such as magnetic refrigeration.

2.1. *Freeze-thaw method*

This method uses vacuum pumping of the liquid hydrogen to first cool the liquid to the triple-point temperature, and then to produce a frozen layer on the surface of the liquid [13–19]. Controlled pressure allows the solid layer to melt slightly and settle into the remaining liquid. Repeating the freeze and thaw cycle numerous times produces a slush from the liquid with a maximum of about 50–65% solid [14,18]. Carney [14] presented the specific mass requirement for vacuum pumping methods (Fig. 1) and vapor volume removed versus slush quality for avarious vacuum pumping production methods (Fig. 2). Niendorf and Noichl [15] was able to produce slush hydrogen with 65–85% solid by compressing the solid during production. They found no correlation between the heat leak or pumping rate and quality of slush produced. Chain [18] suggested that it was not necessary to produce high quality slush at the expense of energy because he expected that the slush would age naturally so that its quality would reach a high value. Sindt et al.[20] found that production of slush in methane was faster for 99% pure methane than for 99.97% pure methane. For the 99% pure liquid, solid particle's formed and settled during vacuum pumping whereas for the 99.97% pure liquid, a solid formed on the surface of the liquid and then pressurized to allow the solid layer to settle. This increase in speed of production and method of formation of the solid particles is attributed to the 1% impurities in the liquid [20]. During slush formation in hydrogen, the minimum pumping rate was reported by Voth et al.[6] to be 1 m^3/s per square meter of liquid surface in the slush production tank. Mann and Ludtke [16] and Daney and Mann [21] obtained an analytical expression for the fraction of vapor removed from the triple-point mixture to produce a given solid content. Mann and Ludtke [16] reported that the particle size distribution had a log normal distribution and the particle sizes ranged from 0.5 to 7 mm with the greatest number in the range of 2.5 to 3.5 mm and also, as the slush ages, the major effect was on the particles in the slush.

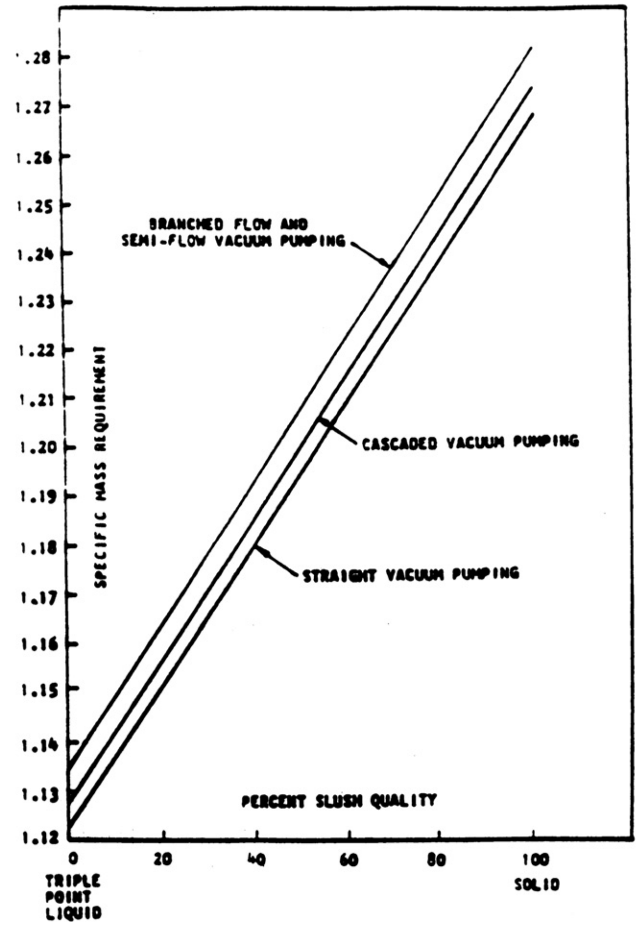

Fig. 1 – Specific requirement for vacuum pumping methods [14]: specific mass requirement (SMR) = initial liquid mass/final mass. Present slush quality (PSQ) = solid mass/total mass initial values for 0 percent quality are SMR needed to produce triple-point liquid: from 20.278 K at 1 atm to 13.8 K at 52 torr. Terminal values for 100 percent quality are the SMR for solid.

2.2. *Auger method*

Slush hydrogen is produced by scraping a frozen layer from inside a tube refrigerated with liquid helium. Slush hydrogen can be produced continuously in an appropriate system [6]. The fresh slush particles are random in size, varying from about 0.1 to 4 mm in the largest dimension and the sizes of both fresh and aged particles vary from 0.5 to 10 mm with 2 mm being the most common size [6]. This method can produce slush hydrogen at a higher pressure than triple-point pressure with less energy needed than for the freeze-thaw method [19].

2.3. *Nozzle expansion method*

Slush hydrogen is produced by Joule-Thompson expansion. The liquid gas is transported under pressure through the