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Thermal analysis of double-pipe heat exchanger in thermodynamic vent system

Zhan Liu [a], Yanzhong Li [a,b,*], Ke Zhou [a]

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing 100028, China

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ABSTRACT

Full use and effective management of cold capacity are significant for improving the performance of heat exchanger in the thermodynamic vent system (TVS). To understand the operation principle of TVS easily, the thermodynamic analysis, based on the ideal gas state equation and energy conservation equation, is detailed introduced. Some key operation parameters are optimized and suggested. As the low mass flow rate and low heat fluxes are involved in flow boiling of the annular pipe fluid, the Kandlikar's boiling heat transfer correlation is selected to predict the flow boiling process, after validated with the related experimental results. One quasi-steady state model is established to investigate the heat transfer performance of double-pipe heat exchanger in normal gravity, with the bulk fluid natural convection, annular pipe two-phase boiling and inner pipe forced convection coupled from outside to inside. Determined by the local pressure and temperature, the fluid thermophysical properties are variable with the pipe length and time. With the variable fluid thermophysical properties, both the static analysis and the transient thermal performance of TVS heat exchanger are investigated respectively. Meanwhile, effects of the external natural convection and the pipe sizes on the thermal and flow performance of heat exchanger are detailed researched and analyzed. Some valuable conclusions are obtained and significant to optimize the TVS heat exchanger design.

1. Introduction

With the inevitable space heat leakage, cryogenic fuel tank pressure will increase rapidly, which is dangerous for tank safety operation [1]. As long duration storage of cryogens in space is greatly important for future exploration mission, some effective pressure control measures have to be conducted. Generally, direct venting is used for reliving the fuel tank pressure for short term storage. While it is applied to long time orbit storage, for instance, several weeks or several months, more propellant boil-losses cost and launch weight will also increase. Therefore, to effectively maintain tank pressure and reduce the propellant venting losses, active pressure control measure must be adopted. By comparisons and verifications, TVS is proven to have a promising application prospect [2,3], with validly maintaining tank pressure through active-venting without resettling.

In the past 20 years, NASA has conducted many theoretical analysis, experimental studies and numerical simulations on TVS. In 1994, Nguyen [4] developed a performance prediction program to investigate the zero-g TVS with different heat transfer modes considered. Based on Nguyen's computational program, Hastings et al. [5] investigated the performance of spray bar TVS for on-orbit LH_2 tank with theoretical analysis. Afterwards, TVS experiments related to LH_2 [6,7], LN_2 [8] and LCH_4 [9] were conducted successively on the multipurpose hydrogen test bed (MHTB) of Marshall Space Flight Center. As different liquid filling heights, heat fluxes, tank pressure control bands, pressurization gases and TVS operation models were detailed experimentally investigated in the ground condition, the tank pressure control has been proven to be better realized by TVS. During the 2008–2010, Ho and Rahman [10,11] have conducted some numerical calculations to investigate the performance of zero boil-off tank by establishing 2D and 3D calculation model. By combining a heat pipe and spray nozzle used in the ZBO tank, it turns out that the tank pressure has been effectively controlled. Recently, Kartuzova et al. [12] presented a CFD spray model to predict the spray flow process with Euler-Lagrange approach to track the spray droplets. Meanwhile, the particle tracking is performed by coupling the spray model with VOF model, with considering the interface heat and mass transportation.

* Corresponding author at: School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: yzli-epe@mail.xjtu.edu.cn (Y. Li).

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Nomenclature

A	area (m^2)
A_u	tank wall area close to the ullage (m^2)
A_l	tank wall area close to the liquid (m^2)
Bo	boiling number
c_{pu}, c_{pl}	gas or liquid specific heat at constant pressure (J/(kg K))
de	characteristic diameter of the annular pipe (m)
dii	inner pipe diameter (m)
dio	outer pipe diameter (m)
dP_f	friction pressure drop (kPa)
dP_g	gravitational pressure drop (kPa)
dP_m	momentum pressure drop (kPa)
dP_t	total pressure drop (kPa)
f	friction factor
G	mass velocity (kg/(m^2 s))
Gr	Grashof number
h	liquid height (m) or enthalpy (kJ/kg)
h_{fg}	latent heat (kJ/kg)
l	pipe length (m)
m	mass (kg)
m_{cir}	circulation mass flow (kg/s)
m_j	two-phase fluid mass flow (kg/s)
m_s	spraying fluid mass flow (kg/s)
Nu	Nusselt number
P	pressure (kPa)
P_{down}	downstream pressure of J-T valve (kPa)
P_{up}	upstream pressure of J-T valve (kPa)
Pr	Prandtl number
q	heat flux (W/m^2)
Q	cold capacity (kJ)
Q_{latent}	latent heat (kW)
$Q_{sensible}$	sensible heat (kW)
R_g	gas constant of HCFC123
Re	Reynolds number
T	temperature (K)
t	time (s)
t_p	pressurization time (s)
T_{spray}	spraying fluid temperature (K)
TVS	thermodynamic vent system
V	volume (m^3)
W	pump power (200 W)
x	gas void fraction
X	Lockhart-Martinelli factor
ΔP_p	lifting height of pump
$(\frac{dP}{dl})_f$	friction pressure gradient (kPa/m)
$(\frac{dP}{dl})_g$	gravitational pressure gradient (kPa/m)
$(\frac{dP}{dl})_m$	momentum pressure gradient (kPa/m)
$(\frac{dP}{dl})_t$	total pressure gradient (kPa/m)

Greek letters

α	heat coefficient (W/(m^2 K))
δ_1, δ_2	wall thickness of inner pipe and outer pipe (mm)
ξ	ratio factor
ε	gas volume fraction
ϕ_v^2, ϕ_l^2	two-phase friction multiplier
η	throttle ratio
κ	adiabatic coefficient, $\kappa = c_p/c_v$
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)

Subscripts

BF	bulk fluid
CBD	convective boiling dominant
FC	forced convection
i	node number
in	inlet
l	liquid
lo	liquid only
max	maximum
min	minimum
NBD	nucleate boiling dominant
NC	natural convection
op	operation
t	tank or total
TP	two-phase
TPf	two-phase flow
u	ullage
v	vapor
W	pipe wall

As the on-orbit testing and technology demonstration are rare, implementation and optimization of spray-bar TVS for mission applications develop slowly. Until now, the technology readiness level is still lower than 5 [13] for LH_2, LOX and LCH_4, so there is still a long way to realize the full application of TVS for future space mission. Although NASA has conducted a lot of research on TVS experiments, there are still few reports on TVS heat exchanger. As the heat exchanger is critical for TVS operation performance, the heat exchanger used for LH_2, LOX and LCH_4, must be different, due to their different cooling ability and density. Moreover, as the two-phase boiling heat transfer occurs in heat exchanger, it is a complex heat transfer and flow process. Therefore, design and optimization of TVS heat exchanger should be given enough attention. Based on the previous research, the thermodynamic analysis of TVS is detailed described in the present study, some operation parameters are optimized. With the bulk fluid natural convection, inner pipe forced convection and the annular two-phase boiling considered simultaneously, one quasi-steady state model is developed to investigate the thermal performance of double-pipe heat exchanger in normal gravity. Iterated with the variable fluid thermophysical properties along the pipe length and time, different effect factors are analyzed and compared. The present study may be beneficial to understand the operation of TVS and provide technical guidance for optimizing the ground-tested TVS heat exchanger design.

2. TVS operation principle

Fig. 1 shows the operation process of TVS [4,5]. One TVS (Fig. 1a) contains a double-pipe spray-bar heat exchanger (Fig. 1c), a Joule-Thompson (J-T) expansion valve, and a circulation pump. To reduce the tank pressure, there are two main operation modes. The first one is the mixing depressurization mode with the fluid extraction from the tank bottom. This mode is only used when the bulk fluid within tank is still subcooled, and only circulation pump activates. When the bulk fluid temperature has reached the saturation temperature corresponding to the tank pressure lower limit P_{min}, the first operation mode will not take effect, so the second operation mode will start with both circulation pump and J-T valve being activated simultaneously. As the first mode only moves the heat capacity from the ullage to the bulk fluid, there is no cold capacity brought into tank, so the bulk fluid temperature always increases. While for the second mode, with the operation of J-T valve, the sat-