International Journal of Heat and Mass Transfer 114 (2017) 796–808

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Inferential framework for two-fluid model of cryogenic chilldown

D.G. Luchinsky [a,*], M. Khasin [a], D. Timucin [b], J. Sass [c], B. Brown [c]

[a] SGT, Inc., Greenbelt, MD 20770, USA
[b] Ames Research Center, Moffett Field, CA 94035, USA
[c] Kennedy Space Center, FL 32899, USA

ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 10 February 2017
Accepted 22 June 2017

Keywords:
Cryogenic flow
Chilldown
Two-phase flow
Optimization
Flow boiling
Heat transfer

ABSTRACT

We report a development of probabilistic framework for parameter inference of cryogenic two-phase flow based on fast two-fluid solver. We introduce a concise set of cryogenic correlations and discuss its parameterization. We present results of application of proposed approach to the analysis of cryogenic chilldown in horizontal transfer line. We demonstrate simultaneous optimization of large number of model parameters obtained using global optimization algorithms. It is shown that the proposed approach allows accurate predictions of experimental data obtained both with saturated and sub-cooled liquid nitrogen flow. We discuss extension of predictive capabilities of the model to practical full scale systems.

1. Introduction

Autonomous management of two-phase cryogenic flows is a subject of great interest to many spacefarers including effective human exploration of the Solar System [1–3]. It requires development of models that can recognize and predict cryogenic fluid dynamics on-line in nominal and off-nominal (i.e. in the presence of mass/heat leaks in the pipe etc.) flow regimes without human interaction.

However, predicting the behavior of two-phase flows is a long standing problem of great complexity [4,5]. It becomes especially challenging when flowing fluids are far away from thermal equilibrium (e.g. during chilldown) and the analysis has to include heat and mass transfer correlations [6–9].

During past decades a number of efficient algorithms [6,10–12] and advanced correlation relations for heat and mass transfer [6,13,14] have been developed for analysis of multi-phase flows [5,9,15–17]. Despite this progress the state of the art in two-phase modeling lacks a general agreement regarding the fundamental physical models that describe the complex phenomena [12]. As a consequence, uncertainties in modeling source terms may ultimately have a bigger impact on the results than the particular numerical method adopted [4].

Analysis of cryogenic fluids introduces further complications due to relatively poor knowledge of heat and mass transfer correlations in boiling cryogenic flows [18–23]. Even less is known about flow boiling correlations of cryogenic fluids in microgravity [3,24]. To address these and other mission critical issues NASA has developed and implemented an impressive program of research, see e.g. [1,2,25,26], that resulted in emergence of space based fluid management technologies.

Under this program a number of important experimental and modeling results have been obtained related to cryogenic two-phase flows (see e.g. [3,22,23,27–35] and references therein). Specifically, two-phase separated flow models were developed for some flow regimes [27,36,37]. A number of optimization techniques have become commercially available for analysis of the model parameters and data correlations [38].

However, small time steps and instabilities [27,37] or implicitness of numerical scheme [39,40] impose substantial limitations on the speed of the solution, efficiency of multi-parametric optimization, and possibility of on-line application. As a result accurate predictions of transient cryogenic flows remain a challenge [23,38] and extensive research is currently under way [3,22].

Some of the grand challenges of this analysis include inference of parameters of cryogenic correlations from experimental time-series data and extension of the results obtained from small experimental subsystems to full scale practical systems.

In this paper we report on the development of separated two-fluid model suitable for fast on-line analysis of cryogenic

* Corresponding author.
E-mail address: dmitry.g.luchinsky@nasa.gov (D.G. Luchinsky).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.097
0017-9310/

Nomenclature

A	cross-sectional area
D	internal pipe diameter
D_h	hydraulic pipe diameter
E	total specific energy
Fr	Froude number
G	mass flux
Gr	Grashoff number
H	total enthalpy
M	model
Pr	Prandtl number
Re	Reynolds number
T	temperature
We	Weber number
X	mass quality
$\dot{m}$	mass flow rate
$\dot{q}$	heat flux
c_p	specific heat for constant pressure
d	time-series data
h	heat transfer coefficient
h_{ld}	dimensionless height of the liquid level
h_{lg}	latent heat of evaporation
p	pressure
u	fluid velocity

Greek symbols

α	gas void fraction
β	liquid void fraction
χ	vapor quality
Γ	mass flow rate of evaporation
κ	thermal conduciviy
μ	dynamic viscocity
ρ	density
σ	surface tension
τ	shear stress
θ	set of model parameters

Subscripts

cb	convective boiling
e	equilibrium
fb	film boiling
gd	dimensionless quantity for gas cross-section
ld	dimensionless quantity for liquid cross-section
mfb	minimum film boiling
n	index for the time step
onb	onset of nucleate boiling
s	satturation
sub	subcooled
w	wall
wg	wall to gas

flows and introduce model-based inferential framework capable of efficient multi-parametric optimization of the model parameters.

We demonstrate an application of this inferential framework to the problem of modeling chilldown in horizontal cryogenic line. This problem has been shown to be a difficult one to solve in the earlier research [38]. Using proposed approach we obtain accurate predictions for transient liquid nitrogen flow both under subcooled and saturated conditions.

The paper is organized as follows. In the next Section we briefly describe the model and algorithm of its integration. In the Section 3 we introduce probabilistic framework for inference of the model parameters, discuss the uncertainties in the source terms and their parameterization. In the Section 4 we introduced constitutive relations used to model source terms. The approach to the inference of model parameters is discussed in Section 5. In the Section 6 we describe an application of the proposed technique to an analysis of cryogenic chilldown in horizontal pipe. Finally, in the Conclusions we summarize the obtained results and discuss directions of future work.

2. Model

We limit our analysis to one-dimensional flow networks having in mind fast on-line applications of the solver. To this end we have developed and tested a number of algorithms [41–48] to see if their speed and accuracy can satisfy requirements of real-time application. It was shown that the nearly-implicit algorithm, similar to one developed in [10], can be applied successfully for on-line predictions of non-homogeneous ($u_g \neq u_l$) and non-equilibrium ($T_g \neq T_l$) flows.

In this section we will describe briefly the corresponding model equations and the algorithm of their integration. Extensive details can be found in [41,42,49,43], see also [47,48].

2.1. Model equations

In nearly implicit algorithm a closed system of equations is obtained assuming equal local pressure values for the both phases [11,50,15]. The corresponding six-equation model consists of a set of conservation laws for the mass, momentum, and energy of the gas (see e.g. [10,51,6,41,42])

$$\begin{aligned}
&\left(A\alpha\rho_g\right)_{,t} + \left(A\alpha\rho_g u_g\right)_{,x} = A\Gamma_g \\
&\left(A\alpha\rho_g u_g\right)_{,t} + \left(A\alpha\rho_g u_g^2\right)_{,x} + A\alpha p_{,x} = -A\alpha g\rho_g z_{,x} \\
&\quad - \tau_{gw} l_{wg} - \tau_{gi} l_i + A\Gamma_g u_{ig} \\
&\left(A\alpha\rho_g E_g\right)_{,t} + \left(A\alpha\rho_g E_g u_g\right)_{,x} = -Ap\alpha_{,t} - \left(pA\alpha u_g\right)_{,x} \\
&\quad + \dot{q}_{gw} l_{wg} + \dot{q}_{gi} l_i + A\Gamma_g H_g
\end{aligned} \tag{1}$$

and liquid phases

$$\begin{aligned}
&(A\beta\rho_l)_{,t} + (A\beta\rho_l u_l)_{,x} = -A\Gamma_g \\
&(A\beta\rho_l u_l)_{,t} + (A\beta\rho_l u_l^2)_{,x} + A\beta p_{,x} = -A\beta g\rho_l z_{,x} \\
&\quad - \tau_{lw} l_{wl} - \tau_{li} l_i - A\Gamma_g u_{il} \\
&(A\beta E_l\rho_l)_{,t} + (A\beta E_l\rho_l u_l)_{,x} = -Ap\beta_{,t} - (pA\beta u_l)_{,x} \\
&\quad + \dot{q}_{lw} l_{wl} + \dot{q}_{li} l_i - A\Gamma_g H_l.
\end{aligned} \tag{2}$$

Here p, α, T, and ρ are pressure, void fraction, temperature, and density of the fluid. E is the total specific energy, $H_{g(l)}$ is the specific enthalpy of the gas generated (liquid evaporated) at the interface and near the wall, g is the gravitational acceleration, u is the fluid velocity, τ is the wall shear stress, and $\dot{q}$ is the heat flux per unit area at the wall and at the interface. The total mass flux per unit volume $\Gamma_g = \Gamma_{wg} + \Gamma_{ig}$ has two components corresponding to the mass transfer at the wall Γ_{wg} and at the interface Γ_{ig}.

The fluid dynamics equations are coupled to the equation for the wall temperature T_w