International Journal of Heat and Mass Transfer 78 (2014) 330–340

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Dynamic process modeling on depressurization by cooling-controlled condensation in a closed chamber

Pengfei He [a], Bo Zhang [a], Chao Zhu [a,*], Zhiming Ji [a], Chao-Hsin Lin [b]

[a] Department of Mechanical & Industrial Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA
[b] Environmental Control Systems, Boeing Commercial Airplanes, Seattle, WA 98124, USA

ARTICLE INFO

Article history:
Received 7 March 2014
Received in revised form 15 June 2014
Accepted 15 June 2014
Available online 23 July 2014

Keywords:
Depressurization
Condensation
Non-condensable gas
Parametric model
CFD

ABSTRACT

It has long been realized that condensation in a chamber prefilled with condensable vapor leads to chamber depressurization, and the condensation rate can be cooling controlled. While the final state can be reasonably estimated based on the thermodynamic equilibrium, the dynamic process of depressurization is not only transient but also in thermal non-equilibrium. This transient and non-equilibrium characteristics, mainly governed by the rate of condensation, has not been satisfactorily modeled, which is due to the complicated coupling mechanisms of heat and mass transfer during the condensation, the presence of non-condensable gas (NCG) within vapor, as well as the complex geometry and properties of chamber and cooling device involved. In this paper, we have conducted an experimental study on depressurization by steam condensation onto an internal cooling coil in a steam-prefilled closed chamber. To reveal various parametric effects on the depressurization process, a parametric model consisting of a set of coupled ordinary differential equations has been established, with some simplified assumptions including lumped heat capacity sub-models for chamber walls, cooling coils and the gas phase. To further explore the thermal non-equilibrium characteristics during the process, a full-field and transient simulation of computational fluid dynamics (CFD) is also conducted using FLUENT with user-defined function (UDF) on boundary of condensation. Both parametric and CFD models consider the existence of NCG that is pre-mixed with the vapor as impurity. By comparison with the experimental measurements, both models reasonably predict the dynamic and asymptotic characteristics of depressurization with time. The CFD simulation indicates an almost instant equilibrium in pressure within the chamber and yet non-equilibrium in temperature with noticeable temperature gradients over the gas phase. The simplified parametric model gives quick predictions of some major parametric effects (e.g., vapor purity, coolant flow rate, and vessel volume) on the rate of depressurization. The detailed mechanistic understanding, gained from proposed models, provides insights essential to the optimized design and operation of the depressurization by cooling-controlled condensation.

1. Introduction

Creating a sub-atmospheric pressure environment in a chamber is essential to some industrial processes such as negative pneumatic conveying and vacuum heat treatment. The depressurization can be realized via various pumping techniques [1,2]. Generally speaking, for normal mechanical pump, the efficiency of vacuum pumping decreases significantly with the depressurization. One alternative approach for chamber depressurization is by condensation. It has long been realized that condensation in a chamber prefilled with condensable vapor leads to chamber depressurization, and the condensation rate can be cooling controlled. Comparing to vacuum pumping, the condensation approach can remove many intermediate processes in energy conversions as conceptually illustrated in Fig. 1. Consequently, the depressurization by condensation presents a great potential in having a much higher efficiency than traditional vacuum pumping whose overall efficiency conceptually is the product of efficiencies of many individual mid-processes:

$$\eta_{condensation} >> \prod \eta_{traditional} = \eta_{boiler} \cdot \eta_{turbine} \cdot \eta_{generator} \cdot \eta_{transformer} \cdot \eta_{pump}$$

In addition, this method of depressurization has unique advantages of simple structure without any moving parts, as well as being noiseless and easier for system volume scale-up. The energy saving is expected to be more significant as system size increases. For

* Corresponding author. Tel.: +1 (973)642 7624.
E-mail address: chao.zhu@njit.edu (C. Zhu).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.06.049
0017-9310/

Nomenclature

A	area
c	specific heat capacity
D	diameter
g	gravity acceleration
h	convective heat transfer coefficient, enthalpy
h_{fg}	latent heat
$\boldsymbol{J}$	diffusion flux
k	thermal conductivity
L	characteristic length
m	mass
$\dot{m}$	mass flow rate, condensate rate
Nu	Nusselt number
p	pressure
Pr	Prandtl number
q	heat flux
R	gas constant
r	chamber radius
Ra	Raleigh number
Re	Reynolds number
S	source term
T	temperature
t	time
$\boldsymbol{U}$	velocity
u	internal energy, velocity
V	volume
Y	species fraction

Greeks

α	mole percentage
δ	condensation film thickness
μ	viscosity
ρ	density

Subscripts

0	initial condition
a	air or non-condensable gas
c	coolant water
ch	chamber
FD	flushing distributor (steam pipe)
i	inlet
l	liquid, condensate water
NCG	non condensable gas
o	outlet
p	pipe of cooling coil
r	radiation
ref	reference condition
sat	saturated condition
v	steam vapor

instance, to vacuum a 30-gallon chamber in a minute (as achieved in this study by condensation), it would require a vacuum pumping capacity of 4 CFM that may be easily available. However, a ten-fold scale-up in size (1000 times in volume) would require a vacuuming capacity of 4000 CFM, which may be manageable by optimized condensation but would be a tremendous challenge and power consumption to vacuum pumping. Although the condensation-induced depressurization needs some small mechanical accessories such as a coolant pump, the energy penalty from those accessories is expected to be small compared to the overall saving.

Despite the apparently simple concept of depressurization by condensation, understanding of this process for the design and control of such a system is far from completed. While the final state of a cooling-controlled depressurization process can be reasonably estimated based on the thermodynamic equilibrium, the dynamic process of depressurization is not only transient but also in thermal non-equilibrium, which is mainly governed by the rate of condensation. The development of a success dynamic process modeling requires a deeper understanding with appropriate modeling formulation on many complicated coupling mechanisms such as heat and mass transfer in cooling-controlled condensation, the transient nature of non-equilibrium during the process, the complication by the co-existence of non-condensable gas (NCG) within vapor, as well as the complex geometry and material properties of chamber and cooling device involved. So far, few modeling efforts on this topic have been reported, with none covering all mechanisms mentioned above. For instance, some dynamic process models have been developed for the dynamic characteristics in depressurization by gas discharging out of a pressurized vessel without phase change [3]; some surface condensation models deal with the coupled mass and heat transfer, yet without the inclusion of NCG [4] nor under the condition of depressurization [5,6]. Recently some modeling efforts include heat and mass transfer coupled phase change to study only pressure drop in micro-channels [7]. Few modeling approaches, especially via transient and full-field CFD simulations, on depressurization by condensation of vapors with NCG have been reported.

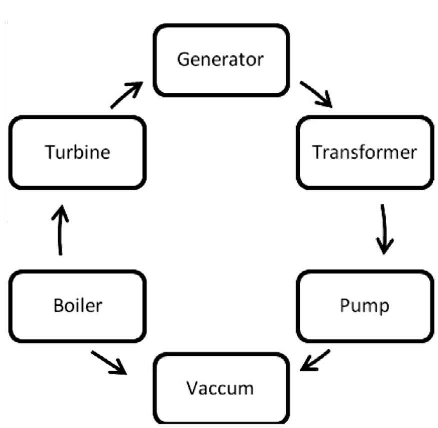

Fig. 1. Energy-conversion processes of vacuuming by pumping or by condensation.

This study is aimed to provide detailed mechanistic understanding and insights essential to the optimal design and operation of the depressurization by cooling-controlled condensation. A depressurization experimental system by cooling and condensation of pre-filled steam in a confined vessel has been designed. The experiment provides sets of data for both mechanistic understanding and validations of our proposed models. A parametric model consisting of a set of coupled ordinary differential equations has been established, which helps to reveal various parametric effects on the depressurization process. The simplified assumptions in the parametric model include the lumped heat capacity approximations for chamber walls, cooling coils and the gas phase. To further quantify the thermal non-equilibrium characteristics of the dynamic process, a transient and full-field simulation of computational fluid dynamics (CFD) has also been conducted. One important step in the CFD modeling is to development of an appropriate boundary condition on cooling coil surfaces where condensation occurs, which is then implemented through a user-defined function (UDF) into the commercial code FLUENT. While