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Research Paper

Transient Heat Transfer Characteristics of Supercritical Fluid during Rapid Depressurization Process

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HIGHLIGHTS

- A visualization study on rapid evaporation of supercritical liquid is performed.
- Transient heat transfer is studied during rapid depressurization process.
- The temperature and NEF are discussed from both experimental and numerical methods.

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ABSTRACT

A combination of experimental studies and numerical simulations is employed to probe into the transient heat transfer phenomenon during rapid depressurization of supercritical fluid in a cylindrical vessel connected to atmosphere via a sudden valve on the top. The effects of initial conditions on heat transfer characteristics are studied, and the morphological characteristics of supercritical fluid are analyzed. Results show: (i) there is a strong re-circulation inside the supercritical fluid with a sudden pressure drop. The heat transfer process is divided into four stages: the initial depressurization stage, the rapid evaporation stage, the nucleate boiling stage and the surface evaporation stage; (ii) under the subcritical state, a higher temperature contributes to a faster temperature drop rate and a shorter fast evaporation time. Moreover, a higher initial pressure leads to a lower equilibrium temperature and a shorter time it takes to reach the equilibrium temperature; (iii) differences are presented in terms of the effect of initial pressure in subcritical and supercritical zones on temperature drop rate with a turn near the critical point. A higher initial pressure gives rise to a higher equilibrium temperature, a slower temperature drop rate and the gradual increasing fast evaporation time; (iv) the experimental data are in good agreement with the calculated results, with a maximum error of 10%.

1. Introduction

In recent years, geothermal energy has received wide attention from scholars all over the world because of its unique stability and wide distribution [1]. The Organic Rankine-Flash Cycle can be used for low- and medium-temperature thermal power generation applications, not only with better system performance, but also with obvious economic advantages. The rapid evaporation transient characteristics of supercritical fluid are one of the key factors affecting the thermal efficiency of Organic Rankine Cycles (ORC) power generation systems [2].

A complex transient heat transfer occurs when the pressure in the vessel or pipe drop suddenly, with the most challenging problems being on high temperature and high pressure [3]. At early stages, the researches both at home and abroad focus mainly on the evaporation of atmospheric pressure to vacuum, with much emphasis on the change characteristics of temperature, pressure and morphology under unconventional depressurization, especially different forms of liquid drops [4–6]. Later, some scholars carry out thorough studies on flash evaporation during depressurization process and fit the representative empirical formula. Shao et al. [7] have experimentally studied the process of vacuum emission of the medium-high pressure liquid, and found the factors affecting the characteristic parameters such as temperature, flash time and flash mass, with a correlation formula proposed. Saury et al. [8,9] probe into the occurrence of flash phenomenon when the pressure of water column suddenly reduces to vacuum, and establish a relationship between flash volume and superheat. Furthermore, elaborate studies have been conducted by Yan et al. [10,11] to systematically investigate the vacuum depressurization flash

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Nomenclature

C_{PL}	specific heat capacity, J/kg·K
Dv	evaporation diffusion coefficient, m^2/s
M	Mole mass, kg/mol
NEF	Non-equilibrium fraction
p	pressure, MPa
r	radius, m
T	temperature, °C
$T(t)$	instantaneous temperature, °C
T_e	equilibrium temperature, °C
T_0	initial temperature, °C
t^*	time of rapid evaporation, s

Subscripts

e	equilibrium condition
0	initial condition

Greek symbols

η	non-dimensional parameter
λ	thermal conductivity, W/m K
ρ	density, kg/m^3

phenomenon and fit a related formula based on the numerous experimental data. Sun et al. [12] make the researches on the thermodynamic characteristics of vacuum depressurization evaporation of atmospheric distilled water through the combination of experiment and theory and elaborate the mechanism of heat transfer at each stage of flash evaporation. Besides, more in-depth studies have been conducted by Liu et al. [13] to investigate the morphology and temperature changes of vacuum evaporation process for mono-component and multi-component droplets. Muthunayagam et al. [14] delve into the fresh water output under different vacuum pressures and initial conditions based on the combination of experiment and simulation, presenting the typical change of flash time. Jain et al. [15] carry out a regeneration experiment and theoretical study of lithium bromide aqueous solution in a falling film regenerator which is suitable for desiccant enhanced cooling system. According to the diffusion evaporation model, Shin et al. [16] have obtained change characteristics of droplets in the process of depressurization. Isao et al. [17] have established a theoretical model for predicting the droplet temperature variation during the pressure drop. In virtue of Mach-Zehnder interferometer and high-speed camera, Peterson et al. [18] have recorded a continuous variation of R11 liquid at room temperature during flash evaporation process and compared the differences and similarities between evaporation and flash evaporation. Zhao et al. [19] have studied flash and freezing process of suspended droplets during rapid depressurization process with special attention to the effect of non-condensable gas on the thermodynamic process. In addition, Zhang et al. [20] employ experiments to investigate the vacuum depressurization flash evaporation characteristics of ethanol solution and record the process of nucleation and crystallization of droplets. Miyatake et al. [21,22] have carried out an experimental study on flash evaporation of the pool water, and pointed out that an exponential decay process is presented in terms of the change of water temperature during the flash process. Moreover, they have measured the flashing time, non-equilibrium fraction, non-equilibrium temperature difference and flash region, and further proposed an experimental correlation of these parameters.

In addition to the existing researches above, some scholars have carried out the preliminary theoretical analysis and numerical simulation of the depressurization evaporation process of supercritical and high pressure fluid [23–28]. However, owing to the complex thermal properties of supercritical fluid, an elaborate and thorough

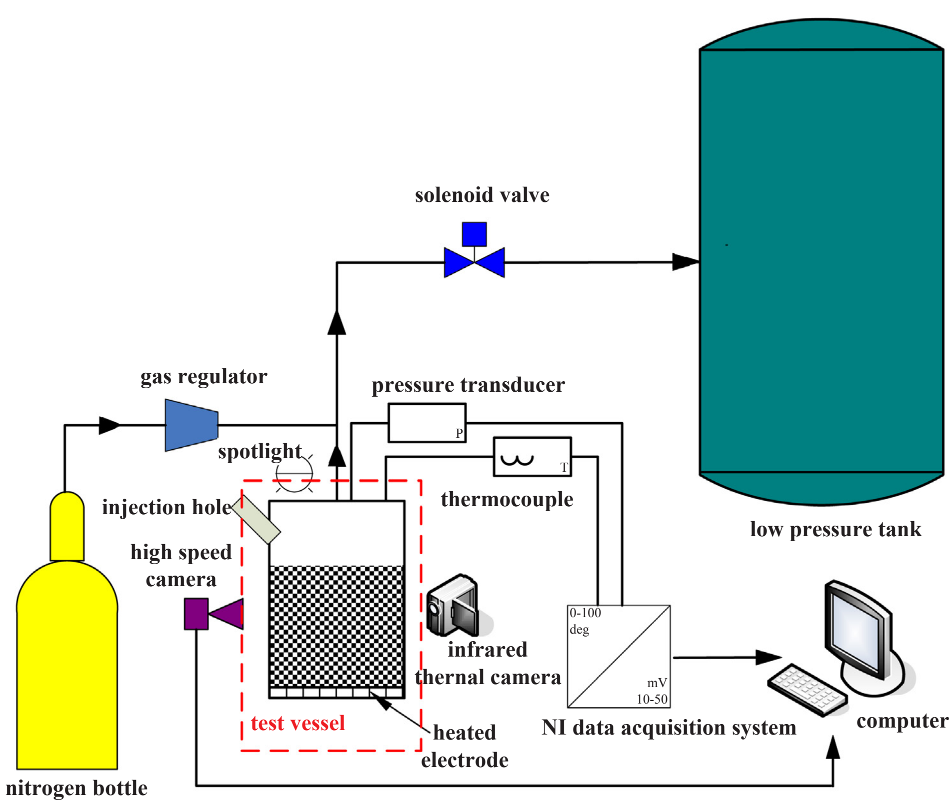

Fig. 1. Schematic diagram of experimental system.