

Rapid Generation of Superheated and Saturated Steam Using Liquid-retaining Porous Materials: Experimental and Numerical Study

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論 文 内 容 の 要 旨

Superheated steam (SH-steam) —steam heated beyond its saturation temperature—has garnered increasing attention due to its unique thermophysical properties, which enable higher thermal cycle efficiency and support drying process. Traditionally, it is produced by further heating saturated steam using superheater coils or specialized heat exchangers. In recent developments, methods such as latent heat storage (LHS), solar superheaters, and micro-gap heating systems have also been employed. Superheated steam finds wide application in power generation, industrial drying, food sterilization, chemical processing, etc. Despite its advantages, several challenges persist, including efficient heat transfer, precise temperature control, and capillary action limitations under high input power conditions.

A liquid-retaining porous block made of lightweight insulating firebrick was used as the core component of the steam generator. Water and ethanol were supplied as working fluids via capillary action. The objective was to investigate the key factors influencing the generation of superheated steam through experimental methods and to further analyze the flow and heat transfer characteristics within the porous block during steam generation through numerical calculations and computational fluid dynamics (CFD) simulations.

Chapter 1 provides a brief introduction to the characteristics of superheated steam and its applications in both daily life and industrial processes. This chapter outlines the key features of existing superheated steam generation devices, including their heat transfer mechanisms, physical dimensions, response time, and energy efficiency, along with their respective advantages and limitations. In the final part, it shows the purpose and objectives of the present study.

Chapter 2 discusses the mechanism by which liquid-retaining porous materials enable the rapid generation of superheated steam. The chapter begins by presenting the design of a superheated steam generator, which primarily consists of a porous block. The application and removal of power enable rapid initiation and termination of steam generation. The relationship between the time required for steam generation, steady-state superheated steam temperature, and heating power was also examined. Comparative experiments were then conducted to analyze the steam generation and reheating processes within porous media. Experimental results provided correlations among the superheated steam temperature, heating wire temperature, and the saturation temperature of the working fluid. To further elucidate the mechanism of rapid steam generation, electrical resistance beneath the heating area was monitored throughout the heating process to determine the presence or absence of dry-out regions. Scanning electron microscopy (SEM) observations revealed that micro-gaps caused by the surface roughness of porous materials significantly influence superheated steam generation. Based on these findings, an improved mechanism was proposed for the rapid generation of superheated steam

using liquid-retaining porous materials.

Chapter 3 compares the superheated steam generation using different working fluids and investigates how their physical characteristics influence response time, energy efficiency, and the maximum achievable heating power limitation. Methylcyclohexane (MCH), a potential hydrogen carrier in chemical storage systems, requires heating and decomposition reactions for hydrogen release. Due to safety and stability considerations, ethanol—having similar thermophysical properties—was used as a substitute for MCH and compared with water under the same heating conditions. Experimental comparisons reveal that thermal conductivity, saturation temperature, specific heat capacity, and latent heat of vaporization play critical roles in determining both the time required for steam generation and the final temperature achieved. A proposed one-dimensional steady-state mass and heat flow transfer model was used to predict the energy utilization efficiency and compared with the experimental results based on measured mass flow rates changing with heating powers. Due to differences in fluid properties, the ratio of sensible to latent heat consumption varies under the same power input, thereby affecting the overall energy utilization efficiency. As discussed in the previous chapter, micro-gaps formed at the heating contact interface of porous materials play a significant role in steam generation. Therefore, a one-dimensional transient thermal conduction model was used to analyze the effects of various gap sizes on heat transfer, including the respective contributions of heat conduction and radiation. The impact of micro-gap thickness, treated as a thermal resistance layer, on the surface evaporation beginning time and heating wire temperature were also evaluated. For ethanol cases, abnormally high temperatures were observed within the porous block at elevated heating powers, leading to the formation of a dry-out phenomenon beyond the liquid supply limit governed by capillary forces. A one-dimensional flow pressure drop model for porous block and micro-gap was introduced to analyze the effects of liquid surface tension and latent heat of vaporization on the maximum capillary-driven heating power. Theoretical predictions were provided and compared with experimental data.

Chapter 4 applies CFD methods to provide a more detailed and intuitive analysis of mass and heat transfer behavior within the porous block under steady-state conditions. The heat transfer at the evaporation interface and the associated mass transfer processes were modeled using user-defined functions (UDFs). These simulations enabled visualization of the two-dimensional distribution of temperature and velocity fields under steady-state operation. This approach allows for the prediction of high-temperature and low-velocity zones, thereby offering design guidance to prevent the formation of dry-out regions. By comparing the temperature and velocity distributions of ethanol and water under high input power conditions, this study highlights both the positive effect of increased power and evaporation rate in enhancing heat extraction from the porous interior, and the negative effect of exceeding the maximum capillary pressure due to increased flow resistance. These insights serve as a design basis for selecting appropriate operating conditions, such as high evaporation rates or low-temperature cooling scenarios.

Chapter 5 provides a summary of the key findings of this research and outlines directions for future work. This study elucidated the mechanisms and limitations of rapid superheated steam generation using liquid-retaining porous materials through both experimental and numerical approaches. The integrated insights offer not only a deeper understanding of coupled heat and mass transfer in porous systems but also practical guidelines for designing compact and efficient steam generators applicable to energy and chemical process industries.