論 文 の 内 容 の 要 旨

論文題目

Investigation of heat and mass transfer mechanisms of water droplets in upward air stream with simultaneous measurements of internal temperature and flow distributions

（温度速度分布同時計測法を用いた上昇流中の液滴における熱と質量の輸送に関する研究）

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Containment sprays are one of the accident mitigation systems used in nuclear power plants to reduce the elevated pressures during the accidents by condensing the steam and cooling the gas atmosphere inside the containment vessel. In recent years, numerous studies have been conducted to investigate the performance of the containment sprays addressing various spray operating parameters or gas component mixing. Overall spray visualization and measurements have also been performed for the characterization of spray clouds. However, up to now, various numerical simulations with sophisticated computational fluid dynamics (CFD) models have not been able to reproduce the depressurization and gas mixture flows adequately. One of the important factors governing the spray depressurization is based on the mechanism of heat and mass transfer between flying liquid droplets and the surrounding gas which are modelled with various empirical correlations.

Since this heat and mass exchange is a complicated process including droplet internal flow circulation, heat and mass diffusion with phase change, the related mechanisms of flying spray droplets behaviors in surrounding gas mixture have not been fully understood yet. Currently, few experimental data has been reported for detailed temperature and flow measurements inside water droplets, especially for the beginning of droplet evaporation during the development of droplet internal circulation, which contains highly transient exchange phenomena and requires high time and spatial resolution of temperature and velocity measurement techniques.

In this study, in order to investigate the heat and mass transfer mechanisms of flying droplets evaporating in surrounding gas experimentally, the high time- and spatial-resolution PIV-TSP technique for two-dimensional simultaneous temperature and flow distributions measurements was improved using an ex-situ calibration method:

1) The calibration results showed that the initial intensity of phosphorescence decay, which varied with the local particle density and laser power, affected the local decay constant as the coefficient of a half sigmoid function. Considering this initial intensity effect, a correlation curve between the temperature and exponential decay constant was obtained by referring to the Arrhenius equation.

2) The improved PIV-TSP measurement technique is free from the errors induced

by local optical noise caused by the non-uniformity of the varying laser power and particle density. The improved ex-situ calibration method can also be applied to various measurement fields having different geometries.

The proposed PIV-TSP technique was applied to measure the temperature and flow distributions inside pendant water droplets evaporating in upward air stream, with an anti-distortion algorithm to correct the optical distortion induced by the curved surface of the droplet. This is the first time to measure the temperature and flow simultaneously inside water droplets at the beginning period of the evaporation in air stream which contains highly transient heat and mass exchange phenomena.

At the beginning of the droplet evaporation air stream, the flow motion developed in evaporating droplets was a toroidal convection pattern (the Hill's vortex) driven by the shear force of the air stream. This kind of flow motion developed within 90 ms in droplets of approximately 2 mm diameter evaporating in 1 m/s air stream.

However, in high temperature air stream, the droplet internal flow developed rapidly with step changes, and the flow was developed in the entire droplet. It can be inferred that the droplet inner convective motion in upward hot air stream is induced by the Marangoni effect due to the gradient in the surface tension and the shear force of air flow, and the droplet internal water mixing can be enhanced by this circulation. The water mixing of droplets and the hot air stream may further change the temperature gradient on the surface after Hill's vortex developed inside droplets, and the internal flow pattern may change again due to the Marangoni convections.

The temperature variations (spatial averaged) of evaporating droplets measured by TSP technique fitted well with the results measured using a K-type thermocouple. No overall temperature gradient can be observed inside droplets from the obtained temperature distributions, neither on vertical direction nor on radial direction, which means that the internal water mixing was strong enough to exchange the gained heat inside the entire droplet.

The experimental data obtained are compared and discussed with the results of droplet heat and mass transfer calculation using some well-known correlations of droplet vaporization. The results indicate that for the calculations of the transient beginning period of water droplet evaporation in temperature range from 20 °C to 80 °C, the widely-used correlations may over-predict the temperature increase of the evaporating droplet significantly, by the heat transfer over-prediction and the mass transfer under-prediction.

With the detailed temperature and flow measurements inside evaporating droplets, our understanding of the heat and mass exchange mechanisms within a droplet's internal flow structures and temperature gradients can be potentially improved.