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# A study of bubble behaviors in the volumetrically heated packed bed

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ABSTRACT

The volumetrically heated packed bed has been widely utilized in modern industry, however, no research on the bubble behaviors in forced convection subcooled boiling was studied. To study the bubble behaviors in the volumetrically heated packed bed, here electromagnetic induction heating method was used to heat oxidized carbon steel balls adopted to stack packed bed, while water was utilized as the refrigerant in the experiment. Bubble behaviors were observed by a high speed camera for particle diameter varying from 8 mm to 12 mm, mass flux varying from 29.3 $kg\ m^{-2}\ s^{-1}$ to 84.2 $kg\ m^{-2}\ s^{-1}$, heat flux varying from 14.5 $kW\ m^{-2}$ to 50 $kW\ m^{-2}$, inlet pressure varying from 0.116 MPa to 0.125 MPa, inlet subcooling varying from 7 k to 9.2 k and porosity = 0.39. Obtained flow visualization images were analyzed. The experimental results indicated that the bubbles were blocked by steel balls and easily attached to the surface of balls, then slipped along the surface of steel balls. There was "regrowth phenomenon" in the packed bed and generated bubbles repeated growth several times in the lifetime. The nucleate boiling was firstly observed in the contact surface. Structures of contact surface had great impacts on the bubble shapes, departure diameter and frequency.



## 1. Introduction

Water-cooled packed bed reactor utilizes the light water reactor technology but uses the new type spherical coated particles as fuel elements. It is a new small type reactor with high economy and inherent safety, and has a great potential in special industries. For example, AFPR-100 (Senor et al., 2007) consists of spherical fuel elements and cooled by single-phase water flow within the particle bed. The concept reactor requires more than 20-year core life. Sümer and Farhang (2008) descript the fixed bed nuclear reactor, fuel element, and criticality calculations. The preliminary neutronics calculations show that the core lifetime can be as long as 17 years. At present, the researches on water-cooled packed bed reactor are in the concept design in the world. So many scientific issues should be studied. Bubble behaviors in forced convective subcooled boiling flow are of considerable interest to nuclear reactors. Subcooled flow boiling heat transfer characteristics are closely related to the bubble behaviors in forced convection subcooled boiling. A visual study of bubble behaviors is helpful to study the boiling heat transfer mechanisms in the packed bed.

Most researches were concentrated in heat transfer enhancement. The packed bed was heated on one side rather than volumetrically heated. For example, Izadpanah et al. (1998) and Jamialahmadi et al. (2005) found that in the channels filled with metallic or non-metallic particles whose working fluid was water, the heat transfer coefficient can be increased by 5–10 times compared with empty channels.

Dryout experiments are based on the issues when the nuclear reactor severely damaged without water. It was investigated by several researchers. For example, Schäfer et al. (2006) studied the pressure distribution inside a boiling particle bed. The crucible had an inner diameter of 125 mm and was filled with oxidized stainless steel balls of 6 or 3 mm diameter. The particles were heated via a two-winding induction coil. The performed boiling and dryout experiment showed clearly that present models without the explicit consideration of the interfacial drag cannot predicate pressure distribution inside a boiling particle bed, not even qualitatively. Atkhen and Berthoud (2006) studied the coolability of a debris bed in multidimensional configurations. Particles were simulated by steel beads with diameters ranging from 2 to 7 mm and were heated by an induction coil. The results showed that the steady temperature overheat up to 200 °C with the increase of power, while the bed was still cooling.

At present, the visual researches of packed bed channels were more concentrated in flow patterns. For example, Ford (1960) was

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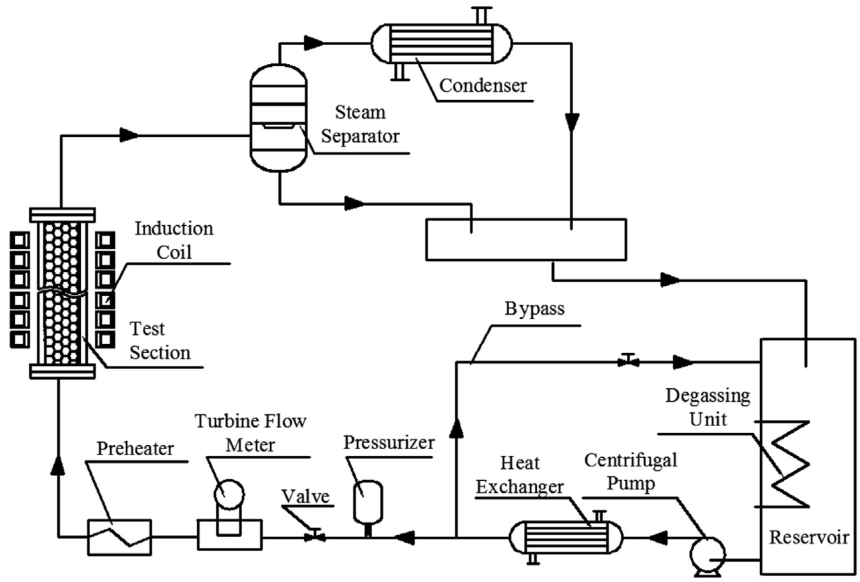


**Fig. 1.** The schematic diagram of experimental setup.

the first to research the flow patterns in packed bed. He observed gas–liquid flow in the packed bed filled with small particles. Based on the two-phase flow distribution in the packed bed, they divided the flow patterns into the single-phase pore flow and the two-phase pore flow. When the mass flux of gas is low, the interspaces were occupied by liquid phase, so the flow pattern was called the single-phase pore flow. When the mass flux of gas was high, the interspaces were occupied by gas–liquid two phases, so the flow pattern was called the two-phase pore flow. Turpin and Huntington (1967), Mazzarino et al. (1987) Based on macroscopic features of the packed bed channel, and divided the flow patterns into bubble flow, pulse flow, spray flow. When the mass flux of gas was low, the bubbles were nearly spherical and dispersed in the continuous liquid phase. The bubble could freely move in the packed bed. With the increase of mass flux of gas, bubbles were elongated and deformed. This flow pattern was called the bubble flow. When mass flux of liquid was medium and mass flux of gas was high, the interaction of two phases was enhanced. Fluids containing more liquid and more gas go through the packed bed in turn. The fluid density was changed in turn and the pulse flow was formed. With the increase of mass flux of gas, the pulse frequency was increased and the density difference between the fluid containing more liquid and the fluid containing more gas was no longer apparent. Further increase the gas mass flux, the spray flow appeared. The spray flow was a continuous gas flow, liquid was suspended or dispersed in the gas. Zhang et al. (2009) was the first to investigate the boiling flow pattern in the packed bed. The experimental section was a rectangular channel filled with 4, 6, 8 mm diameter glass balls. In order to observe, the one side of the channel was plexiglass. In order to provide the heat flux, another side of the channel was a metal plate with many hemispherical projections. The metal plate generated heat by providing the current. They observed the bubble flow, bubble-slug flow, slug flow, slug-annular flow. Wang et al. (2002) was the first to research the bubble behaviors in the pool boiling in the packed bed. The test section was a glass container filled with glass balls and was heated at the bottom. The experimental results showed that the dynamic bubble behavior was significantly affected by the packed bed structure. It was difficult to appear dryout phenomena due to the behavior of the replenished liquid caused by special pore geometry.

No data has been found in the open literature on bubble behaviors in the subcooled flow boiling in the volumetrically heated packed bed, so an experimental setup was built to study it.

## 2. Experimental setup

The experimental setup is shown in Fig. 1. The flow direction in the test section was vertical upward. The water was stored in the tank with 18 heaters. The dissolved gases were removed by heating water to reach saturated. Saturated water flowed through the heat exchanger, flowmeter, pre-heater and the test section by the driving of the pump, and then absorbed the heat generated by the packed bed to change to vapor and liquid mixtures. The mixtures entered the steam separator and was divided into water and vapor separately. The vapor was condensed into water in the condenser. Finally the water condensed from vapor and divided in steam separator flowed back to the tank.

As shown in Fig. 2, the test section was consisted of an annular channel filled balls. The annular channel had an outer diameter of

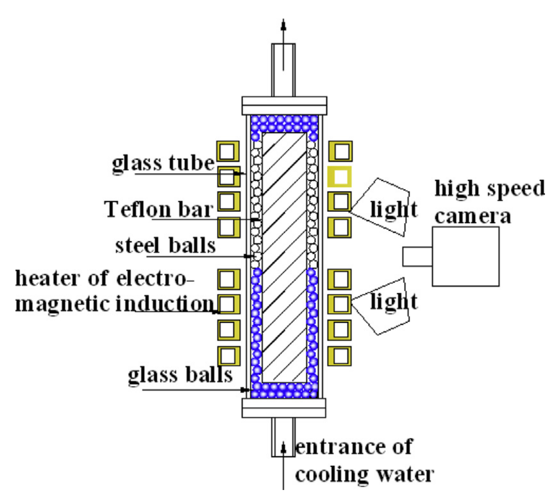


**Fig. 2.** Schematic of packed bed.