Experimental Thermal and Fluid Science 34 (2010) 1346–1352

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental study of the boiling mechanism of a liquid film flowing on the surface of a rotating disc

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ARTICLE INFO

Article history:
Received 4 September 2009
Received in revised form 29 March 2010
Accepted 17 June 2010

Keywords:
Boiling
Rotating disc
Film flow
Centrifugal
Nucleation
Bubbles

ABSTRACT

The boiling mechanism of a liquid film formed on the surface of a smooth horizontal rotating disc was studied using de-ionised water at 2 l/min flow rate, boiling under vacuum at 40 °C and 5–10 °C wall superheat. Visualization experiments were carried out and video films were taken for rotational speeds from 0 to 1000 rpm. It was observed that nucleate flow boiling prevails in the case of 0 rpm (stationary disc). Nucleate boiling was also observed at 100 and 200 rpm with the number of bubbles and the diameter of the bubbles decreasing as the rotational speed was increasing. At 600 and 1000 rpm rotational speeds, vapor bubbles were not observed. The results of visual observation were in agreement with bubble growth analysis which showed that at heat flux values of 40 kW/m^2, conditions for bubble growth are favorable at low rotational speeds (<200 rpm) but are unfavorable at high rotational speeds (1000 rpm).

1. Introduction

The use of centrifugal fields is one of the most promising active techniques for enhancement of heat transfer. Devices, in which liquid films are created due to the centrifugal force on a rotating disc or other surfaces of revolution, are technically suitable for many unit operations involving heat and mass transfer like evaporation, condensation, heating and cooling, liquid–liquid extraction, distillation and absorption. In addition, in space applications where a falling film cannot be achieved in a zero "*g*" environment, the artificial gravity created by the centrifugal force on a rotating disc to generate a thin film can be used.

Centrifugal evaporators are in industrial use today. They are especially useful for heat sensitive products, which must be concentrated at low temperatures and short time to obtain a high quality product. Typical applications include concentration of fruit juices, enzyme solutions, herbal and seasoning extracts, antibiotics, higher class alcohols, oils, etc.

Research on heat transfer, mass transfer and fluid dynamics of rotating discs has been published by various researchers (Espig and Hoyle [1], Rahman and Faghri [2,3], Khan [4], Yanniotis and Kolokotsa [5,6], Jachuck et al. [7], Aoune and Ramshaw [8], Ozar et al. [9], Rice et al. [10], Basu and Cetegen [11]).

Boiling is a complex process, which can take place under a variety of conditions, e.g. pool or forced convection in nucleate or film boiling conditions, at saturated or subcooled liquid temperature, at constant heat flux or constant wall temperature. It is being investigated by many researchers for long time because it is of great importance in many applications. Visual observation, theoretical analysis and modeling have been used to understand the boiling mechanism under various conditions. Gunther [12] was one of the first to study bubble growth rate, maximum bubble diameter, etc. in forced convection boiling. Recently, Thorncroft et al. [13] studied the vapor bubble growth and departure in vertical up-flow and down-flow forced convection boiling. Prodanovic et al. [14] studied bubble behavior from inception to collapse for subcooled boiling of water on upward flow in an annular vertical section. Chang et al. [15] studied the behavior of near-wall bubbles in subcooled flow boiling in a vertical rectangular channel. Quinn and Cetegen [16] studied the heat transfer and bubble dynamics in a film flowing over a rotating disc.

The objective of this work was to experimentally study the boiling mechanism of a liquid film at saturation temperature boiling on the surface of a horizontal rotating disc at low temperatures suitable for heat sensitive liquids like liquid foods. Visual observation of the liquid film during boiling and bubble growth analysis are used to study the boiling mechanism.

2. Experimental work

2.1. Experimental unit

The experimental unit consists of an aluminum disc, 30 cm in diameter and 10 mm thickness, rotating on a stainless steel central

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doi:10.1016/j.expthermflusci.2010.06.007

Nomenclature

Q	liquid flow rate (m^3/s)
N	rotational speed (rpm)
R	disc radius (m)
r	bubble radius (m)
r_c	critical radius (m)
P_s	saturation pressure (bar)
T_g	equilibrium temperature (K)
T_s	saturation temperature (K)
T_w	wall temperature (K)
V_g	specific volume of vapor (m^3/kg)
ΔH_v	latent heat of evaporation (J/kg)
ΔT_e	available liquid superheat (K)
ΔT_{ws}	wall superheat (K)

Greek letters

δ	film thickness (m)
v	kinematic viscosity (m^2/s)
ρ_v	vapor density (kg/m^3)
σ	surface tension (N/m)
ω	angular velocity (1/s)

vertical hollow shaft with 32 mm diameter (Fig. 1). A vertical Plexiglas cylinder 30 cm in height is bolted on the outer diameter of the bottom side of the disc. The bottom end of the cylinder is sealed so that a steam chest is formed on the bottom side of the disc. The whole arrangement is enclosed in an outer stationary Plexiglas cylinder 50 cm in diameter. The feed is introduced at the center of the disc at its boiling point (40 °C), where an attached inverted cup with 3.5 cm radius forms the liquid distributor, through the top end of the hollow shaft. The gap between the disc and the distributor is 0.5 mm. After flowing across the rotating disc as a thin film, the liquid is collected in a tank. Saturated steam at 45–50 °C, which is produced from de-ionised water in an electrically heated boiler, is introduced in the steam chest through the bottom side of the hollow shaft after passing through a steam-condensate separator, that ensures its dryness. Two stationary take-off tubes (scoop pump) are used to remove the condensate from the steam chest. A shell and tube heat exchanger is used to condense the vapor generated from the evaporation of the boiling liquid. Steam and vapor condensate holding tanks and a concentrate holding tank are connected to the main unit. Mechanical seals are used in the points where the fluid streams are flowing from non-rotating to rotating parts to permit operation of the system under vacuum. A DC electric motor with variable speed drive is used to rotate the disc. Two liquid ring vacuum pumps (one for the evaporation side and the other for the condensation side of the disc) are used to remove non-condensables from the system.

The roughness of the disc surface was measured with Perthometer M4P. The mean roughness was 3.8 μm, the mean depth of the roughness was 13.5 μm, the maximum depth of roughness 14.0 μm and the mean height of roughness 7.1 μm.

The data acquisition system, consisted of two stations, is connected to a PC for measurement, control and storage of the data. Station 1 is attached at the bottom end of the rotating shaft and is used for the measurement of the local disc surface temperatures on both sides of the disc using thermocouples (type K) embedded just beneath the surfaces of the disc. Other thermocouples measure the steam and condensate temperature underneath the disc. The thermocouples for the disc surface temperature measurement are placed in 6, 10 and 13 cm from the center so that the middle point temperature in three zones of the disc of about equal area are measured (the total useful heat transfer area of the disc is 0.0596 m^2). A wireless optical transmitter located at the bottom end of the rotating shaft rotating with station 1 is used to transfer the data to a stationary receiver located 10 cm underneath. From the receiver, the data are transferred to the PC. The overall accuracy of the thermocouples and transmitter is ±0.1 °C. Station 2, which is stationary, is used for the measurement of the inlet and outlet temperatures of the fluids and the vapor space temperature. The accuracy of these thermocouples is ±0.5 °C. The flow rate of the liquid was measured with a magnetic flow meter. The rotational speed of the disc is adjusted with a separate controller to within ±10 rpm.

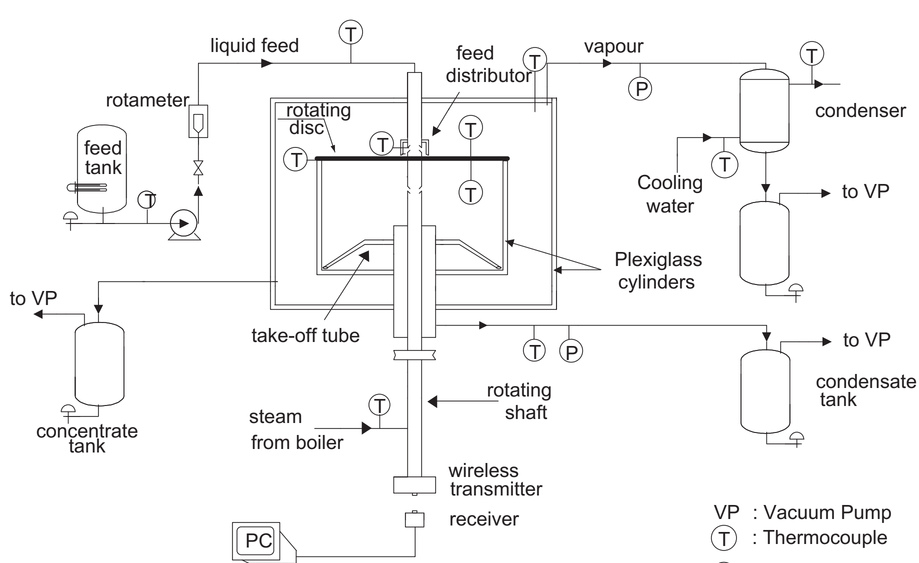

Fig. 1. Experimental set-up.