



An experimental study of solids deposited on the base of a heated vessel at low pressure



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ABSTRACT

The life expectancy of some industrial evaporators is constrained by the rate of corrosion of the heated surfaces, with larger temperatures producing larger corrosion rates. Some process fluids contain dissolved materials that produce solid particles when the fluid is evaporated. These solids can form beds of particles on the heated base of the evaporator vessel or be suspended in the fluid. The presence of these particles may have an effect on the temperature of the heated surfaces and hence their corrosion rate. The effect on temperature of two very different particles are investigated, glass and Caesium Phosphomolybdate particles ($\text{Cs}_3(\text{MoO}_3)_{12}\text{PO}_4 \cdot 14\text{H}_2\text{O}$). The later is referred to as CPM. The glass particles had diameters of 500–600 μm , a specific gravity of 2.2 and a bed depth variation of 0–32 mm. The CPM particles had diameters of the order of 10 μm , a specific gravity of 4.0 and a bed depth variation of 0–50 mm.

The effect of the glass particles was investigated while heating water at a pressure of 50 mbar absolute. The CPM particles were investigated while heating a water solution at a pressure of 65 mbar absolute. The evaporator used was a model industrial boiler slice. The boiler test section was 1 m high, 0.75 m wide and 98 mm long. The evaporator contained 36 electrically heated tubes to simulate the presence of heated coils. The design of the boiler ensured that the tubes, which were 28.5 mm in diameter, were always submerged in a liquid pool. The tube heat flux was maintained at 65 kW/m^2 and the base heat flux varied within the range 0–45 kW/m^2 .

When a base heat flux was applied the glass particles remained within a bed formed on the base of the evaporator, whereas the CPM particles became suspended in the fluid. In both cases, the temperature in the liquid pool is shown to be reasonably constant and close to the free surface saturation value. The bed of glass particles induced boiling on the surface below it at most conditions, increasing the local base temperature and therefore the local corrosion rate. The base remained in free convection outside of the bed, producing lower base temperatures and therefore a lower corrosion rate. The CPM particles did not form a bed on the base of the evaporator and the temperature of the base remained in free convection at temperatures below, or close to, the local saturation value. However, some base heating was evident near the base centre. The presence of CPM type particles is unlikely to affect the corrosion rate.

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1. Introduction

Some evaporators boil fluids that are highly corrosive. The corrosion rate of the materials used to construct these evaporators depends on their temperature. Thus, the life of the evaporator can be extended if the temperatures of their heated surfaces are kept low. One way of achieving this is to heat the fluid at a low pressure, and hence a low saturation temperature. Solids can come

out of solution when these corrosive fluids are evaporated. These solids may form beds of particles on the heated base of the evaporator or they may remain suspended in the fluid. In either case, they may affect the temperature of the heated surfaces and thus the corrosion rate. If the particles enhance heat transfer, the life of the evaporator will be extended, if they degrade it, the life of the evaporator will be reduced. However, if they change the heat-transfer mechanism, the effect is unclear.

Most particle additions have been made in an attempt to enhance boiling heat transfer. Yamaguchi and James [1], Yang and Maa [2] and Ma et al. [3] reported that a suitable amount of

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solid particles present in a boiling liquid can enhance pool boiling heat transfer and boiling hysteresis can be partially, or even completely, removed. Shi et al. [4] suggested that boiling heat transfer can be enhanced by adding solid particles to the liquid, whether fluidized or in a fixed particle bed, and that the enhancement is related to the particle size, the bed depth, the initial bed depth in the fluidized case, and the heat flux applied. Shi et al. [4], concluded that boiling heat transfer characteristics are greatly changed when a particle layer is present on the heated surface and that major changes occur to nucleation, bubble movement and thermal conductivity. Kim and Garimella, [5] used free particles on the base of an evaporator as a boiling enhancement technique. Water was used as the working fluid. Metal particles placed on the heated surface were found to improve boiling heat transfer by providing more active nucleation sites. The enhancement was a function of the number and size of the particles introduced. They found that a mixture of 3 and 6 mm particles improved the average heat transfer coefficient by 115%, relative to a polished surface, within a heat flux range of 20–100 kW/m².

Chuah and Carey [6] presented the effects of a thin layer of unconfined particles on saturated pool boiling heat transfer from a horizontal surface. They used two different types of particles. For both types, vapour was observed to move upward through ‘chimneys’ in the particle layer, tending to fluidise the layer. The experiments showed that the addition of light, low conductivity particles significantly increased the wall superheat relative to those obtained on the same surface and heat flux without particles. However, the addition of heavier, high conductivity particles correspondingly decreased the wall superheat.

Boiling at low pressure has been reported to reduce the heat-transfer coefficient. See, for example, Raben et al. [7]. McGillis et al. [8] attempted to use copper particles to enhance pool boiling for water at low pressure. They found that the presence of particles did not significantly enhance nucleation, probably because of the large critical cavities that occur at low pressure.

The particles investigated in this study are simulants for those that occur in an actual evaporator as a result of the chemistry of the boiling fluid. Their occurrence is an inevitable result of the evaporation process and not an attempt to enhance heat transfer. However, from the literature, it is not clear whether their presence will increase or decrease the temperature of the heated surface. It seems to be the case that particles provide additional nucleation sites that can enhance heat transfer. However, they also provide a flow resistance to liquid trying to reach the heated surface and to the vapour trying to escape from it.

This study was initiated to investigate the changes in base temperature and heat-transfer mechanism that occur in a low pressure evaporator as particles come out of solution. The investigation was carried out on a one quarter scale, thin slice model of an industrial evaporator. The evaporator had a glass front to allow visual information to be obtained. Two significantly different particles were tested for their effect on base temperature, glass and Caesium Phosphomolybdate (Cs₃(MoO₃)₁₂PO₄·14H₂O). The later is referred to as CPM. The glass particles were used to investigate the effect of relatively large particles. They had diameters of 500–600 μm and a specific gravity of 2.2. The bed depth of these particles was varied from 0 to 32 mm. The CPM particles were used to investigate the effect of relatively small particles. They had diameters of the order of 10 μm and a specific gravity of 4.0. The bed depth was varied from 0 to 50 mm.

Tests with glass particles were carried out while heating water at a pressure 50 mbar absolute. The CPM tests were carried out in a solution that contained 1.6 kg of sodium nitrate and 50 g of sodium carbonate in 60 l of water. The sodium nitrate was added so that the CPM particles would behave as they would in nitric acid. The sodium carbonate was added to alter the PH of the solution and

minimise any chemical reactions between the solution and the brass tubes. The later was only partially successful as a ‘greening’ of the test fluid was evident as the tests proceeded. The required quantity of this solution was added to the test facility and tests were carried out at a pressure of 65 mbar absolute. The chemical additions had a minor effect on the fluid properties, which were therefore very similar to those of water, with a water test at 65 mbar producing a difference in base temperature of less than 3 K for the heat flux range of 0–25 kW/m².

2. Description of the test facility

The layout of the test facility is shown in Fig. 1. The vacuum pump was switched on and the test section pressure was reduced to 0.5 bar. This allowed liquid from the storage tank to flow into the test section until the desired liquid level had been achieved. The liquid level was set to approximately 0.85 m. This is the approximate height of T_{s5} in Fig. 2. The vacuum pump was subsequently used to set the required test section pressure. The test-section pressure was measured by a Rosemount 3051 absolute pressure transducer. The required mass of solids was added to achieve the required bed height. The tube heaters were switched on at 90% of full power. After some time, steam was generated. This pushed any remaining air into the hot well before it was expelled to the atmosphere. The liquid entry shut-off valve was opened, the circulating pump was started and the control valves were adjusted when condensate began to accumulate in the hot well. Liquid from the hot-well was pumped by the circulating pump into the test section via the pre-heater. The flow rate was set by adjusting the pump control valves until a steady level was obtained in the hot-well sight glass. The inlet temperature can be set by adjustment of the pre-heater. However, this was not done in the current tests. Steady conditions were achieved in about 3 h, whence the power controllers were set to achieve the required heat flux for the tubes and the base. Test conditions were achieved in a further 30 min before the data was logged. Each instrument was read once per second over a 2 min period to obtain data set a. Conditions were maintained for a further 10 min before the data were logged again to obtain data set b. The power controllers were set to the next condition and the procedure repeated until the necessary heat-flux range had been achieved.

The test section is shown in Fig. 2. Each base heating segment, shown as dashed lines within a heating zone, contained two heater pads. The heater pads were clamped to aluminium heat spreaders that were fixed to the stainless steel base. Heat transfer paste was placed between the heat spreaders and the base wall. The bottom three sets of heater pairs were connected to a single power controller, controller F, as were the next four mirror-imaged heater pairs, which were on controller E. The top two mirrored-imaged heater pairs were also on a single controller, controller D. These independent controllers allowed a distribution of base heat flux to be applied. All of the current tests were carried out at a uniform heat flux. The power to each heater group was measured on a power metre that was accurate to ±1% of reading. Each tube contained a rod heater, Fig. 2. The power to the tubes was controlled in a manner similar to the base, see McNeil et al. [9]. The tube heat flux was set to 65 kW/m² for all of the tests. Temperatures within the evaporator were measured by k-type thermocouples. The thermocouple locations in the test section are shown in Fig. 2. NB: only the right side of the evaporator contained thermocouples. The thermocouples were classified into 2 groups. The first group are referred to as the stream thermocouples. These were located within the liquid pool. The ‘stream’ was considered to start at the free surface, flow down the centre line and on to the base of the test section, move across the base and up the side of the base,

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