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Condensation of Steam on the Underside of a Horizontal Surface
in the Presence of Air and Helium*

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ABSTRACT

Experiments and data analysis for the condensation of steam on the underside of a horizontal surface in a closed vessel are described. Previously reported results for film condensation with air as a noncondensable gas are reviewed and compared with new data with helium as the noncondensable in the same apparatus. Observations, including photographs of the condensate configurations, related to the occurrence of dropwise condensation are also discussed. It is noted that data reproducibility over long periods of time were possible only with film condensation and that with dropwise condensation condensing surface temperatures exhibited large nonuniformities and random fluctuations with time. The well known mass transfer calculational model for accounting for the presence of noncondensable gases had been shown previously to be successful with air. The same model when applied to the helium data was not successful except for small gas contents. It appears that the suppression of convection that would be expected to occur with the less dense gas is counteracted by convection induced by fog or mist formation.

MASTER

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INTRODUCTION

The initial purpose of the research described herein was to obtain information related to certain hypothetical nuclear reactor accidents during which condensation on the underside of horizontal surfaces plays an important role [1,2]. Results from this program related to film condensation, including the effect of the presence of air as a noncondensable gas, were discussed in Ref. [3]. Steam was condensed on the underside of a horizontal surface in a closed vessel; pressures ranged from 0.31 to 1.24 MPa, heat fluxes from about 0.05 to 0.7 MW/m², gas contents from the maximum the system could contain at 1 atmosphere to negligible amounts. The present paper extends the results obtained previously by including data with helium as the noncondensable gas, photographs of the condensate configurations obtained, as well as observations related to dropwise condensation and data reproducibility. The data obtained, and their analysis with respect to engineering prediction methods, have a variety of other applications both within and outside of nuclear reactor technology. Condensation on the underside of horizontal surfaces in the presence of noncondensable gases occurs above the sodium pool in pool type liquid metal cooled nuclear reactors, and similar heat transfer paths exist in water cooled reactors. Aside from the expected interest in such information for design of industrial heat exchange equipment in general, recently proposed schemes for the cooling of electronic devices are also related.

Heat transfer data for condensation on the underside of flat horizontal surfaces are not very plentiful in the available literature compared, for example, with studies for the inner and outer surfaces of tubes, both horizontal and vertical, and for vertical plates [4]. Perhaps the first reported data collection was that of Popov [5] in 1951 who obtained heat transfer correlations for condensation on the underside of horizontal surfaces, but

very few details of this effort are available. The first detailed studies were published by Gerstmann and Griffith [6] for film condensation of Freon-113 on both inclined and horizontal surfaces at atmospheric pressure. A smaller data set with water was also obtained. They applied a detailed mathematical model to their data which resulted in a correlation which reproduced their data quite well. Their research did not include the effect of noncondensable gases except to note that the presence of gas (air) had a very noticeable effect on the formation of pendant drops on the condensate film and on the stability of the film. As will be noted further below, our experiments with steam and both air and helium did not exhibit any effect of gas content on film behavior. Kroger and Rohsenow [7] investigated condensation of potassium vapor on the underside of a horizontal surface in the presence of the noncondensable gases helium and argon, but did not obtain data for negligible noncondensables. They found that in the absence of significant natural convection, that was possibly active with the heavier gas argon, a simple one dimensional mass diffusion model adequately predicted their data.

A relatively large amount of research has been reported related to the cooling of heat generating electronic components by immersion in suitable liquids that are allowed to boil. The vapor generated is dissipated in various types of configurations some of which closely resemble condensation on the underside of horizontal surfaces in a closed vessel. A comprehensive survey of these electronic cooling schemes is given by Bar-Cohen [8] with details of some of the related research reported in Refs. [9] to [11]. More recent electronic cooling related studies are the film condensation experiments of Yanadori et al. [12,13,14] with Freon (R113) and Methyl alcohol as the liquids and with argon, helium, neon and nitrogen as noncondensables. Their experiments are very similar to those described in this paper except

that an important aspect of their data was the flow of condensate down along the inner vertical walls of the containing vessel. Our experiments were with water over much larger pressure and gas content ranges without significant condensate flow along the vessel walls and include observations related to both dropwise and film condensation with photographs of the condensate configurations that occurred. In addition, more attention was given to testing predictions of the effect of noncondensables.

APPARATUS

Detailed descriptions of the apparatus and operating procedures can be found in Ref. [3]; only a brief summary will be given here. As shown in Fig. 1, the main portion of the apparatus consisted of a 137 mm ID cylindrical pressure vessel. The inside vertical height of the vessel was 240 mm. The top of the vessel was sealed with a water cooled steel block to which was attached an 8 mm thick copper condensing surface with three embedded thermocouples for measuring the condensing surface temperatures (Fig. 2). The condensing surface was highly polished and carefully cleaned before installation. The vessel was loaded with 2.49 KG of demineralized water for all experiments reported here and in Ref. [3]. Under nonboiling conditions the distance between the top of the liquid pool and the condensing surface was 76.2 mm; the condensing surface area was 14900 square mm. During operation the water was boiled by 15 electrical cartridge heaters extending into the pool from the vessel bottom. Pressures were measured with one of two pressure transducers selected according to the pressure range; temperatures within the pool, gas-vapor space, and along the outer surfaces of the vessel were measured with thermocouples.

The vessel contained two view ports through which the condensing surface and the top of the boiling pool was observed and photographed. Measurable amounts of noncondensable gas was removed or added to the vessel by separate gas venting and gas injecting systems. The actual system gas contents were determined by the procedure described in Ref. [3] which, in brief, consists of measuring the pressure and temperature of the system when in thermal equilibrium without heat addition and calculating gas content based on vapor pressure and Dalton's and Henry's laws. In Ref. [3] gas contents were reported as mass of gas per mass of water in units of PPM. In this paper a potentially more general measure of gas content is also noted; mass of gas per unit volume of gas-vapor space at nonboiling conditions. The appropriate conversion factor is 1 PPM equals 2.2 g/m^3 . This measure of gas content is considered more general because it is independent of the total mass of water in the system which for gases that are not very soluble in the liquid (e.g. air and helium) does not significantly affect the active gas content.

OPERATING PROCEDURES

Steady state condensing heat transfer data sets were obtained at constant pressure and gas content over a range of heat flux or temperature difference. Operation for obtaining these data sets required special procedures for assuring steady state conditions and reproducibility. Because of the relatively large thermal mass of the apparatus, the attaining of steady state conditions was time consuming; it was not usually possible to obtain more than one set of data at constant pressure and gas content during one day's operation. The long periods of operation with daily shutdowns and restarts would occasionally result in changes in the mode of condensation as observed through the view ports and/or by noting that the data obtained was not consistent with

those obtained previously. As a result, it was an important part of the operating procedure to check for reproducibility with previously obtained data at the beginning and end of each day's operating period. The conditions under which nonreproducibility of data occurred is an important aspect of the experiments and as a result is discussed separately below.

The three thermocouples embedded in the copper condensing plate (Fig. 2) were used to measure condensing surface temperatures. These temperatures, which included a small calculated correction for conduction through the plate, always indicated a nonuniform distribution along the surface with the smallest values close to the center of the condensing surface. The direction of cooling water flow through the spiral flow channels in the condensing block did not have a significant effect on this temperature distribution. An average surface temperature was calculated by weighting the three measurements according to radial location and used to form a heat transfer temperature difference with the boiling temperature. The surface temperatures also fluctuated with time in an apparent random manner; time average values from 100 measurements taken over a 30 second period were used for the data sets. In general, for the reproducible data sets (film condensation), nonuniformities of measured surface temperatures were rarely larger than 10% of the calculated heat transfer temperature difference and maximum to minimum fluctuations with time were less than 5% of the temperature difference. Surface temperature nonuniformities and fluctuations were not always as small with the nonreproducible data sets (dropwise condensation).

REPRODUCIBLE VS NONREPRODUCIBLE DATA SETS

The reproducible data sets obtained, as verified by the procedures described above, always pertained to film condensation as observed through the

vessel's view ports. The typical appearance of film condensation on the underside of the horizontal surface is shown in the photographs of Figs. 3 and 4. (The camera angle used for all photographs is shown in Fig. 1.) The surface is completely covered by a continuous liquid film. Liquid falls from the film as a result of the growth and eventual detachment of a relatively small number of pendant drops. Figure 4 shows such a detachment of a pendant drop. The hemispherical diameters of the pendant drops are about 1/2 cm. The number and size of the pendant drops, which appeared to move along the liquid film in a random manner, did not noticeably change over the large range of conditions (pressure and gas content) of the experiments. The rate of drop detachment was clearly related to the rate of heat transfer.

The nonreproducible data sets always pertained to dropwise or mixed mode condensation. Figure 5 shows a photograph of what is meant here by dropwise condensation, with a small area closest to the camera which appears to be in partial film condensation. Figure 6 shows a different type of partial film condensation; about 1/2 of the condensing surface appears to be non wetted but no small drops can be detected in these locations.

The most frequent identifiable cause of non-reproducibility was inadvertent system contamination caused by liquid eventually contacting the packing material surrounding the view ports. The effect of contamination of this type is illustrated in Fig. 7 which displays condensing heat transfer data with negligible gas content. The correlating line drawn through the reproducible data sets represents the negligible gas film condensation correlating equation derived in Ref. [3] which, except for a relatively small but as yet unexplained effect of pressure, is close to the correlating equation of Gerstmann and Griffith [6]. The data shown for the contaminated systems, which as observed through the view ports appeared as dropwise or mixed mode condensation, could rarely be reproduced from one day's operation to the next.

Reproducible film condensation data with air as the noncondensable gas was obtained at pressures of 0.31, 0.62 and 1.24 MPa (Ref. [3]). With helium as the noncondensable gas, reproducible data above pressures of 0.62 MPa could not be obtained. At higher pressures, film condensation with configurations as shown in Figs. 3 and 4 could not be maintained; instead the partial film condensation configuration of Fig. 6 would eventually result and the data would no longer be reproducible.

FILM CONDENSATION WITH NEGLIGIBLE GAS CONTENT

The negligible gas content heat transfer data of Ref. [3] actually had a small but measurable amount of gas present in the system according to the procedure used to determine this quantity. The procedure determines gas content in the entire enclosed system, which includes regions that are not active during condensation. These regions are the small volumes associated with the tubing for the gas venting and injecting system and attached to the pressure transducers. That a gas content was negligible was determined by noting that below a certain value the presence of gas in the system no longer had an effect on the condensing heat transfer data. For the data of Ref. [3] with air as the gas this value was about 30 PPM (66 g/m^3). For the more recent data with helium as the gas the corresponding value was about 2 PPM (4 g/m^3).

The heat transfer data with negligible helium gas content are included in the graphs of Figs. 8 and 9 which display all of the film condensation data obtained with this gas. The curves on these graphs identified as "Ad Hoc Correlation" (see Appendix) represent the negligible gas (air) correlation of Ref. [3]. The Gerstmann-Griffith correlation, from which the Ad Hoc correlation is derived, is also shown on the graphs. The negligible gas data with

helium is judged to be sufficiently in agreement with the negligible gas data of Ref. [3].

FILM CONDENSATION WITH NON-NEGLECTIBLE GAS CONTENT

Film condensation heat transfer data with air as the non-condensable gas was successfully correlated in Ref. [3] by use of an analogy between natural convection heat and mass transfer. It was assumed that mass transfer controlled in the space between the boiling pool and condensate liquid film, and that heat transfer across the film could be predicted by the negligible gas correlation with an appropriate temperature drop through the film. With air as the gas, natural convection results because of the heavier density of air compared to water vapor.

A similar model (see Appendix) was used in an attempt to correlate the heat transfer data with helium as the non-condensable gas -- i.e. the data of Figs. 8 and 9. Since the density of helium is much less than that of water vapor, natural convection in the mass transfer controlled region should not occur. Instead the model would require treating this region as one in which mass transfer of water vapor occurs by molecular mass diffusion through a stagnant gas. This model is essentially the same as that used by Kroger and Rohsenow [7] for condensation of potassium vapor in the presence of helium, except that with water the thermal resistance of the liquid film cannot be neglected as it can with the liquid metal. Satisfactory predictions with this calculational model were obtained only with helium gas contents less than about 6 PPM (13 g/m^3). For higher gas contents, measured heat fluxes were larger than predicted by factors as high as about four. Furthermore, ratios of measured to predicted heat fluxes over the range of data obtained did not exhibit consistent trends with gas content or temperature difference

indicating that the simple stagnant gas model cannot serve as a basis for an empirical correlation of the data. These difficulties can be noted from the data of Figs. 8 and 9 by observing that the data sets for gas contents of 6.2 and 8.1 PPM (14 and 17 g/m³) agree with each other, and thus suggest the occurrence at higher gas concentrations of an additional mechanism for heat transfer not accounted for by the stagnant gas mass diffusion model.

An explanation for these difficulties in data interpretation is believed to be related to the formation and movement of mist within the gas-vapor space. The occurrence of fog or mist was clearly observed through the vessel's view ports. Its density appeared to increase with increasing gas content; its motion, although generally in a downward direction, consisted of localized swirls similar to the circulation patterns of natural convection. These qualitative visual observations indicate that a model based on vapor mass transfer through a less dense stagnant gas cannot be correct when gas concentrations are too large; fog generation and its motion result in convective currents and probably affects density distributions as well. Inclusion of these additional complex mechanisms in a calculational model has not been attempted as yet.

Fog formation was also observed with air as the noncondensable gas. However, since it was possible to correlate the data by use of an analogy between natural convection mass and heat transfer it would appear that additional convection resulting from the presence of fog did not have a significant effect on the condensing heat transfer.

DROPSIZE OR MIXED MODE CONDENSATION

As noted previously, data obtained with dropwise or mixed mode condensation was not reproducible. As a result, data correlation was not attempted.

As to be expected, heat fluxes were always higher than comparable values under film condensation. In addition, temperature nonuniformities along the condenser surface as measured by the three thermocouples shown in Fig. 2 were much larger and fluctuated widely with time so that proper time and space average values could not be defined in a meaningful manner. These nonuniformities of condensing surface temperatures were much more severe with helium as the noncondensable than with air.

Nonuniformities of measured condenser surface temperatures are illustrated in Table 1. The table lists measurements taken directly from the data sheets for experiments at comparable conditions, viz. at 1.24 MPa with average condensing heat fluxes of about 6 KW. Maximum, minimum and time average values from the three thermocouples are shown for various helium contents. The measurements are based on 100 instantaneous readings of each of the thermocouples over a period of about 30 seconds. For comparison, a comparable data set with film condensation is also listed. The last column of the tabulation shows a measure of the nonuniformity as a fraction of the calculated condensing temperature difference (saturation temperature minus radial average surface temperature) as used to correlate the film condensation data. The nonuniformities illustrated are typical of the dropwise condensation data obtained with helium at pressures ranging from 0.31 to 1.24 MPa.

CONCLUSIONS

The major results of this study can be summarized as follows:

- (1) Film condensation of steam on the underside of a horizontal copper surface (see Figs. 3 and 4) in a closed vessel can be maintained over large ranges of pressure, heat flux and noncondensable gas (air and helium)

cent. The heat transfer data obtained with this mode of condensation are reproducible over long periods of time which include intermediate shutdowns and start ups of the experiments as well as apparatus disassemblies and assemblies.

(2) With film condensation, the well known mass transfer calculational model for accounting for the presence of noncondensable gas was successful with air as the gas. The same model when applied to the helium data was not successful except for small gas contents. It appears that the suppression of convection that would be expected to occur with the less dense gas is counteracted by convection induced by fog or mist formation.

(3) System contamination resulted in dropwise or mixed mode condensation (Figs. 5 and 6). Reestablishment of film condensation could not be achieved without apparatus disassembly and a thorough cleaning of the entire system internals including a repolishing of the condensing surface. However, continual operation with dropwise condensation over very long periods of time was not attempted.

(4) Data with dropwise condensation was not reproducible from one day's operation to the next, and there were large nonuniformities and fluctuations in time of the measured condensing surface temperatures, especially with helium as the noncondensable gas.

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Appendix. Film Condensation Correlations

The Gerstmann-Griffith correlation for negligible gas content is an empirical fit of complicated calculations for condensation on a quasistable liquid film adhering to the underside of a horizontal surface [6]. This correlation is in the familiar form of a Nusselt number as a simple power function of a Rayleigh number, based on an idealized maximum liquid film thickness δ as the reference length. The liquid film thickness is given by

$$\delta = \sqrt{\sigma/[g(\rho_f - \rho_v)]} \quad (A1)$$

where σ is the surface tension, g is the gravitational constant, ρ_f and ρ_v are the liquid and vapor density, respectively. The Nusselt number is then defined as

$$Nu_{film} = q\delta/(k\Delta T) \quad (A2)$$

where q is the condensing heat flux and k is the liquid thermal conductivity. The Rayleigh number is defined by

$$Ra_{film} = g(\rho_f - \rho_v) h_{fg} \delta^3/(k\nu\Delta T) \quad (A3)$$

where h_{fg} is the latent heat of vaporization and ν is the liquid kinematic viscosity. The temperature difference ΔT refers to the saturation temperature minus the condensing surface temperature. Except for ρ_v and h_{fg} , physical properties are for the liquid film. The correlation for the Rayleigh number range appropriate to the data of Ref. [3] and this paper is

$$Nu_{\text{film}} = 0.69 Ra_{\text{film}}^{0.2} \quad (10^6 < Ra_{\text{film}} < 10^8) \quad (\text{A4})$$

The predictions of the Gerstmann-Griffith correlation shown on Figs. 8 and 9 were obtained from Eq. (A4) with film properties evaluated at the arithmetic mean of the surface and saturation temperatures.

The data of Ref. [3] exhibited an effect of the system pressure which could not be accounted for by the Gerstmann-Griffith correlation. In Ref. [3] a simple ad hoc correlating equation was derived for the data by multiplying Eq. (A4) with an empirical power function of the pressure. The resulting correlating equation was

$$Nu_{\text{film}} = 0.787 P^{0.464} Ra_{\text{film}}^{0.2} \quad (\text{A5})$$

where P is the pressure in MPa. This correlation is shown in Figs. 7 to 9.

For the case of non-negligible gas content, mass transfer of the condensing vapor in the space between the boiling pool and condensate liquid film must be considered. In the absence of natural convection, mass transfer occurs by molecular diffusion of the vapor through a stagnant gas. It can be shown that the total vapor mass flux for this ideal case is obtained from the relationship

$$\omega = (X_{\text{gas},o} / X_{\text{gas},av}) (1 - \exp(-\omega)) \quad (\text{A6})$$

where $X_{\text{gas},av}$ is the average gas mole fraction in the vapor-gas space, $X_{\text{gas},o}$ is the gas mole fraction at the liquid film interface as determined from the interface temperature and ω is given by

$$\omega = N_{A,stag} L / (D C_{av}) \quad (A7)$$

where L is the length of the gas/vapor region between the boiling pool and condensate liquid film, D is the binary molecular diffusivity for the gas/vapor mixture, C_{av} is the average total molar concentration and $N_{A,stag}$ is the total molar flux of water vapor for the stagnant gas case. All quantities except $N_{A,stag}$ are known from the experimental data; ω can then be determined from Eq. (A6) by simple iteration from which $N_{A,stag}$ is obtained. The condensing flux is then obtained by multiplying $N_{A,stag}$ with the enthalpy change from the boiling pool surface to the liquid film interface.

The stagnant gas model would be expected to be reasonable for the steam/helium mixture, since the density of helium is much less than that of water vapor. For the steam/air mixture, however, the density of air is about sixty percent larger than that for water vapor indicating that natural convection will be important invalidating the stagnant gas assumption. Indeed, in Ref. [3], the steam/air data was successfully correlated taking into account natural convection based on a heat-mass transfer analogy.

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Table 1. Selected 1.24 MPa Data Illustrating Nonuniformities of Condenser Temperatures with Dropwise Condensation and Helium as the Noncondensable
(Note: Last Case Tabulated is with Film Condensation for Comparison)

HELIUM CONTENT (PPM)		HEAT FLUX (KW)		CONDENSER THERMOCOUPLE READINGS AT RADIAL LOCATIONS INDICATED (C)							NONUNIFORMITY AS FRACTION OF ΔT		
				3.52 CM			2.63 CM			1.46 CM			
				MAX	MIN	AVG	MAX	MIN	AVG	MAX		MIN	AVG
19.2	6.3	137	120	130	115	94	103	80	70	73	0.72		
9.0	6.2	160	151	156	150	135	143	117	110	114	0.92		
5.5	6.4	160	152	157	151	139	147	126	120	123	0.81		
NEGL.	6.4	170	166	168	167	161	164	158	151	153	0.59		
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NEGL.*	6.2	146	138	140	138	133	136	136	132	135	0.10		

* Film condensation case.

FIGURE CAPTIONS

- Fig. 1. Schematic of Apparatus (Gas Venting/Injection and Pressure Transducer Lines not shown)
- Fig. 2. Details of Condensing Surface
- Fig. 3. Typical Film Condensation as Photographed Through View Port (Note: View Port ID is 44.5 mm. Figure 1 shows camera angle.)
- Fig. 4. Film Condensation Showing Pendant Drop Detachment (see Fig. 3 Note)
- Fig. 5. Typical Dropwise Condensation (see Fig. 3 Note)
- Fig. 6. Partial Film Condensation (see Fig. 3 Note)
- Fig. 7. Effect of System Contamination on Condensing Heat Transfer at 0.62 MPa and with Negligible Noncondensables ("Severe" contamination from graphite impregnated packing material. "Moderate" contamination from failure of electrical insulating sleeves.)
- Fig. 8. Film Condensing Heat Transfer Data at 0.31 MPa and Various System Helium Contents
- Fig. 9. Film Condensing Heat Transfer Data at 0.62 MPa and Various System Helium Contents

SEIN, ET AL
FIG. 1

STEIN, ET AL
FIG. 2

STEM, ET AL
FIG. 7

Steam to Air
Fig. 8

STEIN, ET AL
FIG. 9