Journal of the Korean Nuclear Society
Volume 18, Number 4, December, 1986

Forced Flow Dryout Heat Flux in Heat Generating Debris Bed

Jong Hee Cha and Moon Ki Chung
Korea Advanced Energy Research Institute
(Reseived October 14, 1986)

열을 발생하는 Debris층에서의 강제대류 Dryout 열유속

차 종 희 · 정 문 기
한국에너지연구소
(1986. 10. 14 접수)

Abstract

The purpose of this study is to obtain the experimental data of the forced flow dryout heat flux in a heat generating debris bed which simulates the degraded nuclear reactor core after severe accident. An experimental investigation has been conducted of dryout heat flux in an inductively heated bed of steel particles with upward forced flow using coolant circulation system under atmospheric pressure. The present observations were mainly focused on the effects of coolant mass flux, particle size, bed height, and coolant subcooling on the dryout heat flux. The data were obtained when carbon steel particles in the size distribution 1.5, 2.5, 3.0 and 4.0 mm were placed in a 55 mm ID Pyrex glass column and inductively heated by passing radio frequency current through a multiturn work coil encircling the column. Distilled water was supplied with variation of mass flux from 0 to 3.5 kg/cm^2 s as a coolant in the tests, while the bed height was selected as 55 mm and 110 mm. Inlet temperature of coolant varied by 20°C and 80°C. The principal resuls of the tests are: (1) Dryout heat flux increases with increase of upward forcing mass flux and particle size; (2) The dryout heat flux at the zero mass flux obviously depends on the particle size as previous studies; (3) The forced flow dryout heat flux in the shallow bed is somewhat higher than that in the deep bed,

요 약

이 연구의 목적은 가혹한 사고후 손상된 원자로심을 모의한 열을 발생하는 데브리층에서의 강제대류 드라이아웃 열유속을 실험적으로 얻고져 한 것이다. 이 연구에서 냉각재 순환장치를 사용하여 대기압하에서 냉각재가 상향 강제대류하는 유도 가열된 강구 입자층에서의 드라이아웃 열유속을 얻었다. 이 실험에서는 주로 강제대류 드라이아웃에 대한 질량유속 · 입자크기 · 입자층의 높이 및 냉각재의 서브쿨링의 영향이 관찰되었다. 실험은 입자직경이 1.5, 2.5, 3.0 및 4.0mm의 탄소강입자를 55 mm 내경의 Pyrex 유리용기에 넣어 고주파유도 전류를 통해 가열하여 이루어졌다. 냉각재로서 증류수를 질량유속 0~3.5Kg/m^{2}s로 변화시키어 공급하고 층의 높이는 55mm와 110mm, 냉각재유입온도는 20°C와 80°C로 변화시켰다. 주요 실험결과는 다음과 같다. (1) 드라이아웃 열유속은 상향 강제대류 질량유속과 입자크기내의 증가에 따라 증가한다. (2) 질량유속이 없는 경우 드라이아웃 열유속

은 기존 연구결과와 같이 입자직경에 의존한다. (3) 얕은 입자층에서의 드라이아웃 열유속은 깊은 입자층의 것보다 얼마간 높다.

1. Introduction

Especially in the pressurized water reactor, the core can be significantly damaged by an uncontrolled loss of coolant through a break in the reactor coolant system caused by failure of the emergency core cooling system. Inadequate cooling of the core with the unavailability of a heat sink will cause the temperature rise of the fuel and structual material with time, and finally it leads to core melt with release of hydrogen and fission gases. The molten fuel flows down into the coolant region, and then it will freeze while entrapping pieces of cladding in it. During this melting-freezing period, the thermal stresses resulting from quenching will cause the fuel to fragment.

Under severely degraded state, the core may behave as a debris bed containing heated particles of various sizes and shapes. Dryout in a heat generating debris bed takes place when the local bed temperature increases above the saturation temperature of the liquid. At this point it is generally assumed that the bed would go through a temperature excursion and may reach the bed melting temperature. The containment of such a severe accident depends on the coolability of a heat generating debris bed. In the aftermath of the Three Mile Island accident, interest in degraded core sequences and debris bed coolability in the light water reactor was intensified.

If a complete blockage of the core occurs, the core may be submerged in a pool of liquid, cooling of the core can only occur with a countercurrent flow configuration. On the other hand, if there is no massive impervious blockages from near the inlet to the core, maintaining a coolable geometry of the core will depend on the flow rate that can be sustained through the core with available pressure difference across the core.

Numerous experimental data were obtained in the early stages of the investigation of the dryout under pool boiling condition with various parameters/1, 2, 3, 4, /, and some analyses of a heat generating debris bed were reported /1, 2, 3, 5, 6, 7/. However, there is only limited information reported in the open literature on forced flow dryout in debris bed.

The behavior of a volumetrically heated porous bed sudject to forced flow cooling in the subcooled and saturated flow regimes was studied by Naik and Dhir/8/, however, they did not extend the test condition of dryout. To determine the minimum flow rate necessary to prevent bed dryout, Squarer and Peoples/9/ carried out a series of tests on an inductively heated particulate bed using water.

They conclude with their test that typical flow velocity required to prevent bed dryout at a power density of 1. 1w/g in an 8 in. -deep bed is 0. 001 ft/s. Tsai et al. /10/ experimentally investigated the dryout heat flux in an inductively heated bed of metal particles with forced flow from bottom of the bed. They used Freon-113 as coolant with mass flux of 0 to 3. 11 kg/m^2 s. They found that the dryout heat flux increases with increasing mass flux and it asymptotically approaches the total evaporation energy of the flow.

The objective of this study is to provide qualitative forced flow dryout information for heat generating debris bed through the performance of a series of tests involving the pertinent parameters: mass flux; particle size; height of bed; and inlet temperature of the coolant at atmospheric pressure.

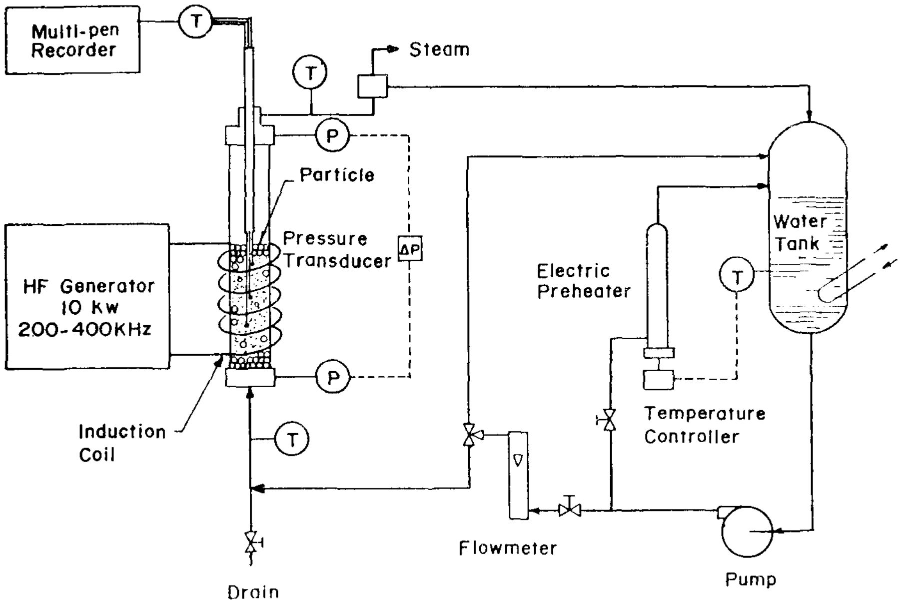

Fig. 1. Schematic Diagram of Test Loop

2. Test Description

The main parts of the experimental setup are the test loop which is included debris bed, high frequency induction heater with a work coil, and related instruments. The test loop consists of a pyrex glass tube filled with steel particles, a reservoir containing distilled water, a centrifugal pump, an electric preheater, a flowmeter and piping. A schematic diagram of test loop is shown in Figure 1.

The particulate bed was contained in a 55mm ID, 280 mm height pyrex tube and inductively heated with a 72 mm ID multiturn work coil. The work coil was powered by a 10 kW power output and 200 to 450 kHz Lepel high frequency generator. Carbon steel particles in the bed are supported by a stainless steel screen at the bottom of the test section. The stainless steel reservoir tank containing 350 liters of distilled water at room temperature is connected to the inlet of the pyrex tube through a 0. 5 HP centrifugal pump and a 3 kVA electric preheater. Subcooled coolant flows up through the particulate bed via flowmeter by a pump. Preheater, if any, was used for heating the subcooled coolant. Liquid portion of the coolant outflow from the bed returned to reservoir while separated steam portion at the separation tee was released to the atmosphere. The temperature of coolant at the reservoir was controlled by an immersion cooler.

The instrumentation consists of the thermocouples with multipen X-Y recorder for measuring temperatures, rotameter for measuring the flow rate of coolant, and pressure transmitter for measuring the pressure difference between inlet and outlet of particulate bed. The temperature at different locations in the bed was measured by using six of 30 gage chromel-alumel thermocouples which were carried in thin alumina capillary tubes and connected to a multipen recorder as shown in Figure 2.

Prior to each run the selected particles were rinsed using acetone more than three times and shaken vigorously during rinsing. The washed and dried particles were poured into the pyrex

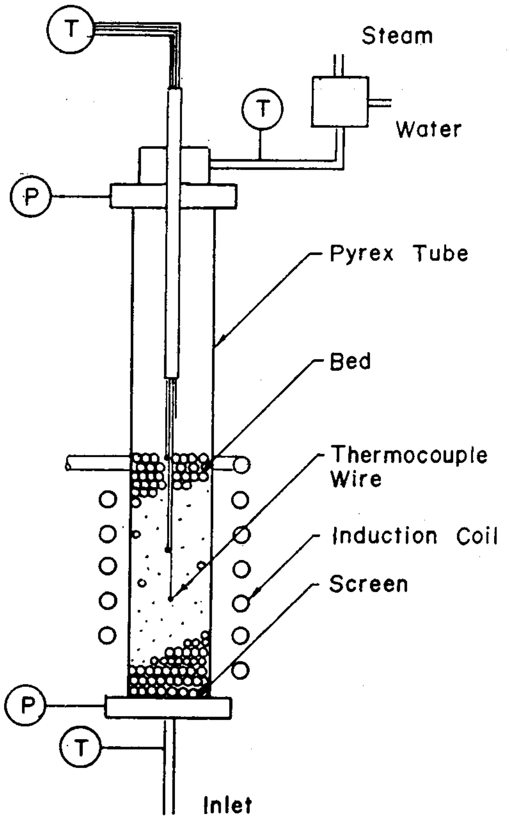

Fig. 2. Schematic Presentation of Test Section.

tube to a certain height.

Calibration of the heat generation rate in the particulate bed as a function of generator power setting was made with measuring the temper atures at inlet and outlet of flow, and flow rate of the coolant through a bed for each run. The heat generation rate, E, in the particulate bed was determined as follows:

$$E = GC_{pf}(T_0 - T_i) \quad (1)$$

where G is flow rate of coolant, C_{pf} is specific heat of coolant, $(T_0 - T_i)$ is temperature difference between inlet and outlet coolant flow. The convection heat losses from the surfaces of the test section were found to be very small and were neglected.

The tests were conducted according to the following procedure:

(1) Turn on the pump and adjust the valves to have desired flow rate and inlet temperature while turning on the induction heater for warming-up.

(2) The power was increased in steps. At each power setting, time was allowed enough so that the dryout of the bed would occur if the heat generation rate was high enough.

(3) Dryout of the bed was observed visually by glowing as well as by noting the sharp rise in the temperature of one or more of the thermocouples.

(4) Power was turned off after dryout was observed. The observation was repeated at least once more under the same test conditions.

(5) Repeat steps 1 through 4 under different test conditions.

The following table lists the selected parameters and test conditions for the experiments. All tests were were done at atmospheric pressure.

3. Results and Discussion

The power density distribution within the bed was obtained by heating the dry bed and comparing the heating up rate at the different spatial positions. An axial power distribution of bed is plotted in Figure 3. The power level of upper and lower portion of the bed to the average is approximately 75 % and the power level of central portion of the bed to the average is indicated 112 %. The radial distribution of power is nearly flat.

Visual observation revealed the strong motion of heavy nucleate boiliing in a liquid zone above the bed, however, there was no channeling appeared at top of the bed through the tests. The dry hot spot was detected at the position of approximately two third height from bottom of the bed.

Experimental parameters known to influence forced flow dryout are condition of coolant,

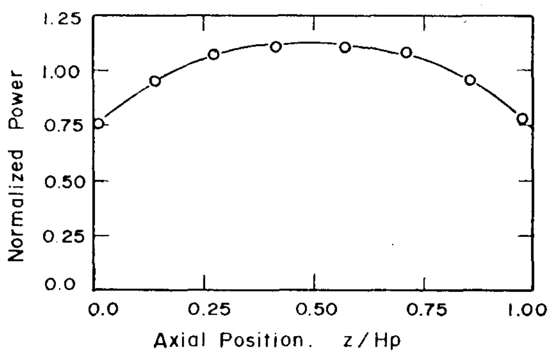

Fig. 3. Axial Power Distribution.

configuration of bed, materials of bed composition and properties of coolant. The focus of this work is placed on those parameters such as mass flux, particle size, height of bed and subcooling of coolant.

3.1. Effect of Particle Size on Dryout Heat Flux at Zero Mass Flux

During the tests, dryout heat fluxes at zero mass flux were measured with four particle sizes for 110mm bed height and 80°C subcooling of coolant. Figure 4 shows the influence of particle size on the dryout heat flux for the case of zero mass flux. The results show that the dryout heat flux is increasing with increasing particle size as previousinvestigators obtained. It appears that Lipinski's model/6/ predicts in a good agreement with measured data. It can also be observed in Figure 4 that as the particle size increases above 3mm, the dryout heat flux is to be within that of Zuber's range of critical heat flux for a flat plate on pool boiling/11/.

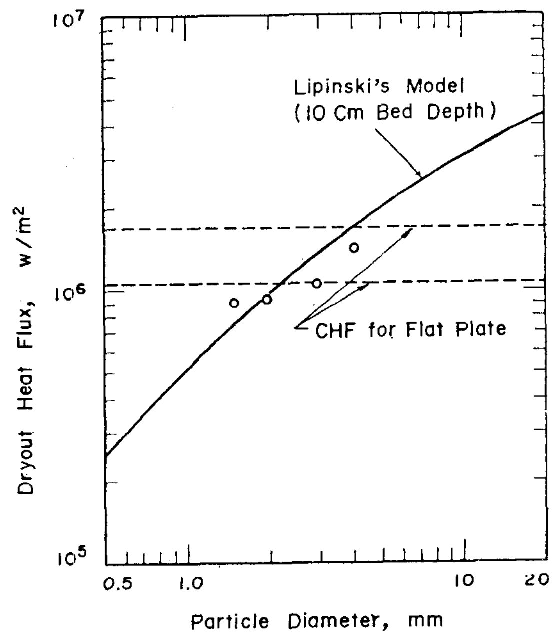

Fig. 4. Dryout Heat Flux vs. Particle Dia-meter at Zero Mass Flux.

3.2. Effect of Mass Flux on the Dryout Heat Flux

Forced flow generally enhances the heat transfer in the particulate bed compared with the natural convection, so that the dryout heat flux

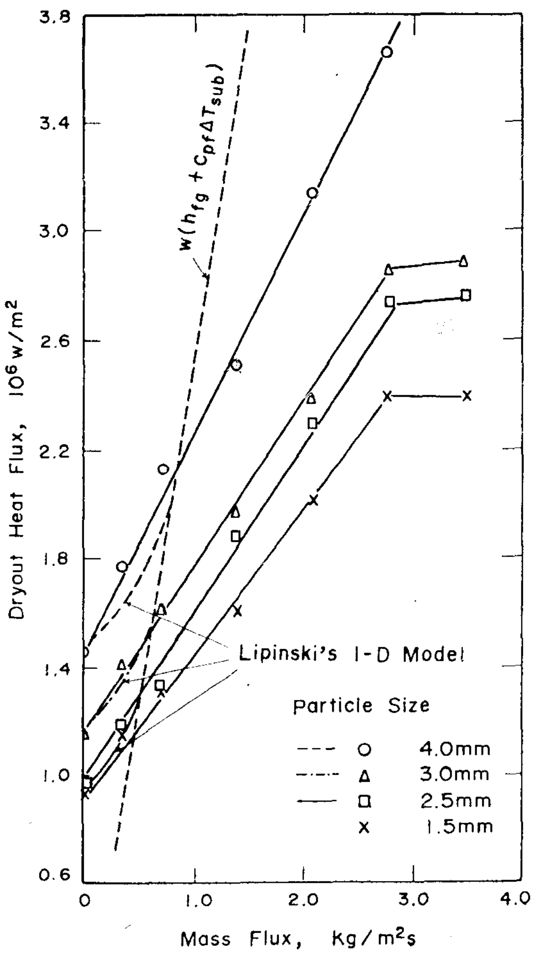

Fig. 5. Forced Flow Dryout Heat Flux vs. Mass Flux.

at the bed can be increased by forcing upward flow through the bed. Figure 5 shows the variation of dryout heat flux as a function of mass flux of coolant for each particle size. The dryout heat flux increases with increasing the mass flux.

Theoretically the dryout heat flux asymptotically approaches to $w(h_{fg}+C_{pf}\Delta T_{sub})$, which is the energy flux required to evaporate all the incoming subcooled coolant. In the region of mass flux between 0 and 1kg/m^{2}s, Figure 5 indicates that Lipinski's 1-D model/7/ best predicts the data trend and magnitude. Beyond 1kg/m^{2}s mass flux, however, the trend of increasing rate of dryout heat flux is extremely deviated from both of Lipinski's curve and total evaporation energy curve. Tsai et al. presented in their study on forced flow dryout that the dryout heat flux asympotically approaches the total evaporation energy of the inlet flow. In the higher mass flux region, however, test data of this study show that forced flow dryout heat flux is much lower than the value of total evaporation energy as shown in Figure 5. It means that not all the inlet liquid evaporates when it flows through the bed. It should be noted that there is some carry-over liquid flow

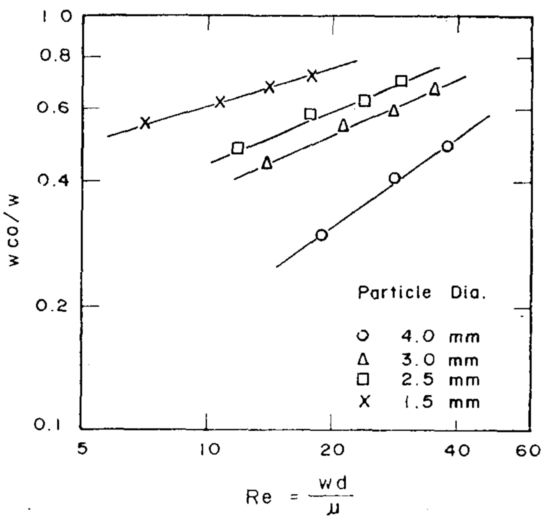

Fig. 6. Reynolds Number Vs. Carry-over Rate

in the outflow even it appears the dryout phenomenon. Figure 6 shows the relationship between carry-over mass flux and Reynolds number. It can be seen that carry-over mass flux increases with increasing Reynolds number.

It can be expressed that the actual forced flow dryout heat flux, q, follows:

$$q_{dw}=(w-w_{co})(h_{fg}+C_{pf}\cdot\Delta T_{sub}) \quad (2)$$

where w is total mass flux, w_{co} is carry-over mass flux, h_{fg} is heat of evaporation, and ΔT_{sub} is subcooling of inlet flow. It can be assumed that

$$w_{co}=f(w,\ d,\ H_p) \quad (3)$$

where d is particle diameter, and H_p is bed height.

Forced flow dryout heat flux also increases with increase with increase of particle diameter under fixed mass flux condition.

3.3. Effect of Bed Height on the Forced Flow Dryout Heat Flux

Affecting the overall resistance to fluid flow

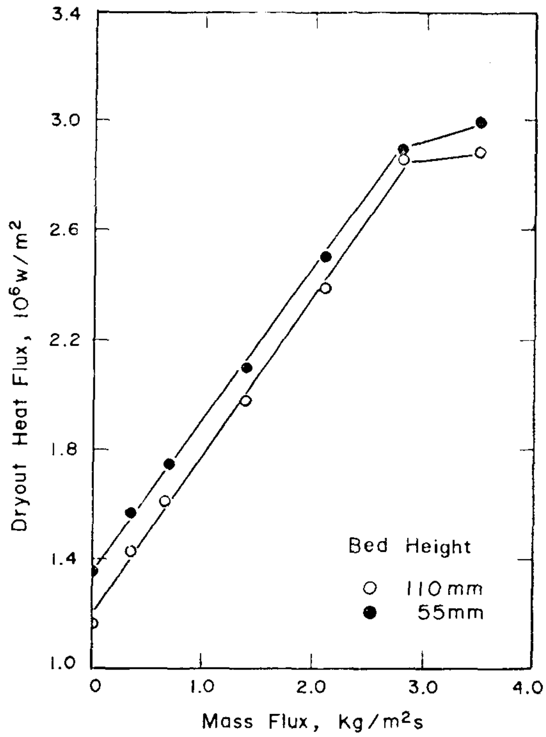

Fig. 7. Effect of Bed Height on the Dryout Heat Flux (Particle Size; 3.0mm).

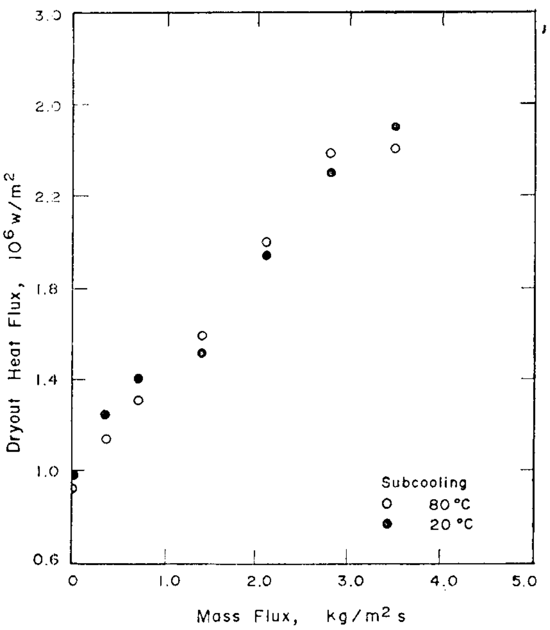

Fig. 8. Effect of Subcooling on the Dryout Heat Flux.

through the bed, that the dryout heat flux increases with decrease in bed height is called shallow bed in case of pool boiling/12/. Similar trend was observed in the case of forced upward flow dryout as shown in Figure 7, and it shows that dryout heat flux in the shallow bed is somewhat higher than that in the deep bed. It appears that this finding can be attributed to the reduction of resistance through the shallow bed. As the permeability of the bed is increased, the heat transfer can be enhanced.

3.4. Effect of Subcooling on the Forced Flow Dryout Heat Flux

The increase in heat flux of subcooled liquid flow will be proportional to the ratio of the sensible energy needed to heat the upflowing coolant to saturation temperature and the latent heat of vaporization, that is, $C_{pf}\Delta T_{sub}/h_{fg}$. Figure 8 shows the effect of subcooling on the dryout heat flux for the upflowing coolant. It can be observed that there is no appreciable difference between the two different subcooled liquids. According to above relation, $C_{pf}\Delta T_{sub}/h_{fg}$, only a 10% increase in the heat flux should occur for water subcooling of 80°C. Such increase is within the experimental error band. As long as $C_{pf}\Delta T_{sub}/h_{fg}$ is significantly smaller than unity, the effect of subcooling of the liquid flow on the dryout heat flux would be small. So this effect should be negligible.

3.5. Correlation of Experimental Data

The following form was chosen for an empirical formula to correlate the experimental data for the dryout heat flux due to forced convection of coolant,

$$q_{dw}=Kw^a q_{do} \tag{4}$$

where q_{dw} is the forced flow dryout heat flux (W/m²), w is mass flux of coolant (kg/m²s), q_{do} is the dryout heat flux at zero mass flux (W/m²), and K and a are empirically derived

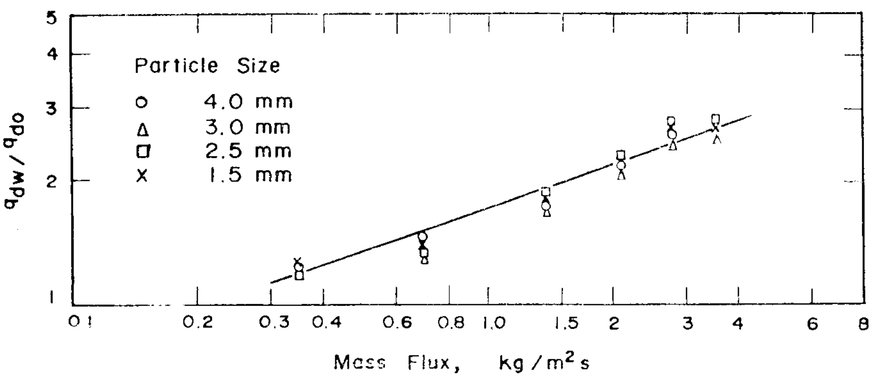

Fig. 9. Effect of Mass Flux on the Flow Dryout.

constants. In the subject test, it can be chosen that $K=1.73$ and $a=0.35$ as shown in Figure 9.

4. Conclusions

A series of tests has been performed with the objective to further the understanding of forced flow dryout in the heat generating debris bed. Tests were conducted with distilled water at atmospheric pressure. The following results can be drawn from this experimental study.

(1) The dryout heat flux increases with increase of upward forcing mass flux and particle size. In the lower mass flux region, less than $1 kg/m^2s$, the dryout heat flux asymptotically approaches the total evaporation energy of the inlet flow, however, in the higher, in the higher mass flux region, greater than $1 kg/m^2s$, the dryout heat flux is much lower than the value of total evaporation energy.

(2) The dryout heat flux at the zero mass flux obviously depends on the particle size as previous studies. It was onfirmed that the present data were in reasonable agreement with Lipinski's model.

(3) The forced flow dryout heat flux in the shallow bed is somewhat higher than that in the deeper bed. The effect of coolant subcooling is negligible in this experiment. There was no channel apeared at the top of the bed during the tests.

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