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Measurement of The Thermal Contact Conductance in Nuclear Fuel Element

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핵 연료 요소내의 접촉 열전도도 측정

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Abstract

Experiments to predict the thermal contact conductance between the fuel pellet and cladding have been performed, which is important to determine the temperature distibution within the fuel rod. UO_2 and Zircaloy-2 are used in these experiments. The measuring apparatus is composed of a presser which controls the contact pressure, a thermometer with S.S sheathed thermocouples, a vacuum pump, pellet and cladding rods, and two heating devices, etc. The thermal contact conductances were measured with varying the contact pressure and surface roughnesses of UO_2 and Zircaloy-2 bars. The results show that an increase in the contact pressure and a decrease of surface roughness resulted in increase of the thermal contact conductance. Finally, a fitting correlation has been established and compared with widely-used correlations.

요 약

핵연료봉내의 온도 분포를 결정하는데 있어서 중요한 핵연료소자와 피복판 사이의 접촉 열전도도를 결정하기 위한 실험을 수행하였다. 이 실험에 사용된 측정장치는 접촉압력을 임의로 변화시켜 줄 수 있는 가압기와 열전대, 진공펌프, 핵연료소자, 봉형태의 피복관, 그리고 두 개의 히터 등으로 구성되어 있다. 접촉 열전도도는 UO_2 소자와 Zircaloy-2 피복관 사이의 접촉 압력과 표면 조도를 변화시키면서 측정하였다. 그 결과 두 물체사이의 접촉압력이 증가함에 따라, 그리고 표면이 매끄러울수록 접촉 열전달계수는 증가하였다. 실험에서 얻은 값을 가지고 상관식을 만들었으며 일반적으로 사용되고 있는 상관식과 비교하였다.

I. Introduction

It is well known that the power generated in a nuclear fuel rod is limited by maximum permissible temperature. Thus, we need detailed informations about the temperature distribution within a nuclear fuel rod for the design of fuel and the determination of reactor operation range. In the nuclear fuel rod, there is the gap between fuel pellet and cladding in the fresh fuel rod. But they come to contact with each other by cladding creep down and pellet swelling after long reactor operation. Morever, fuel and cladding of PHWR and most of experimental reactors are made to be contacted with each other from the onset. When this situation occurs, the heat is transported directly by the conduction through contacted regions on the fuel and cladding surfaces. It occurs difficult problems to calculate the nuclear fuel rod temperature distribution because of these complexity of temperature changes on the contact surfaces. Many experiments have been attempted to measure the thermal contact conductance for the optimal design of nuclear fuel rod by using the uranium pellet and Zircaloy-2 or stainless steel, which are the general fuel components in the nuclear power plants.[1, 2, 3] In this experiment, we attempted to measure the thermal contact conductance between the depleted UO_2 pellet and Zr-2 at vacuum state. The measurements were performed with changing the surface roughness and changing the contact pressure in range from 2000 to 4000 psia. The reference temperature was maintained about 300 F at 0.1-0.3 torr vacuum. As results, an increase in the contact pressure and a decrease of surface roughness resulted in the increases of thermal contact conductance. And results are fitted to produce the correlation as functions of the contact pressure and the surface roughness, which is compared with the well-known correlation.

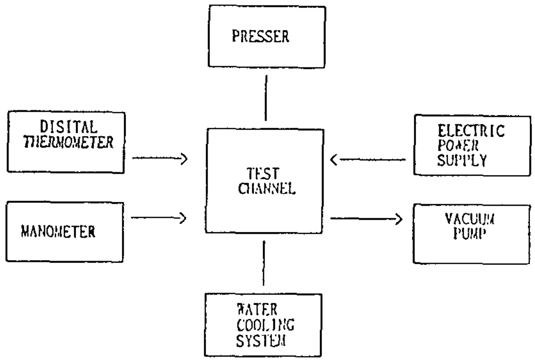

Fig. 1. Blockdiagram of Experiment System for Measure of the Thermal Contact Conductance

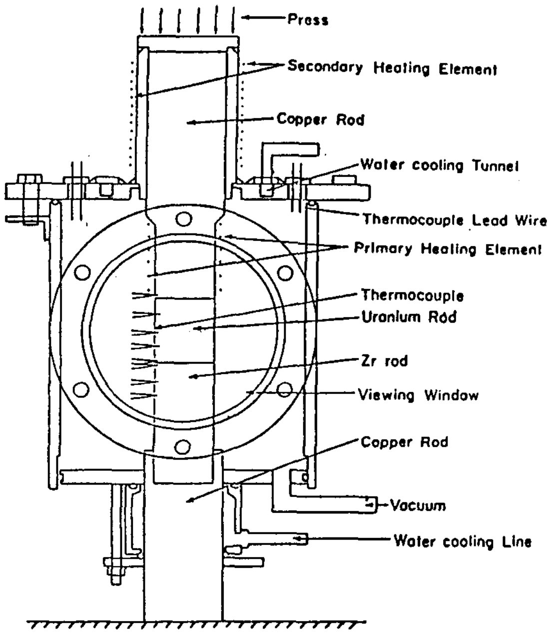

Fig. 2. Gap Conductance Measurement Schematic

II. Apparatus and Method

II-1. Apparatus

The experiment system is composed of presser, test channel, vacuum pump, digital thermometer, manometer, electric power supply, and water cooling system. The block diagram of the experiment system is represented in Figure 1. Test channel having volume of 2.6 liters is designed to allow observations the inside of test channel through the viewing window. It is shown in Figure 2. The two heaters which can heat both inside and outside of test channel are installed to generate the heat flux from UO_2 pellet to Zr-2 cladding. The contact surface temperature between UO_2 pellet and Zr-2 cladding is controlled within 1 °F accuracy by controlling the test channel heat flow. And the lower part of the test channel that sealed up to make vacuum state can be movable to permit the change of distance when the pressure is exerted to the sample. It is designed that the cylinder of test channel can be movedby connecting to rubber packing between cylinder and lower plate of test channel. The presser that uses a principle of a lever can exert the force to the vertical direction continuously. This presser is less convinent than the oil-press-method presser, but it is proper in this experiment because the constant weight can be retained in long period and so the pressure does not change through the thermal expansion in UO_2 pellet and cadding meterials. Other installed experimental devices are the band type heaters that can supply heat to the sample materials, 0.5mm diameter thermocouples that can measures the sample temperature distribution, the rotary pump that can retain the vacuum state, the manometer that can measure vacuum condition, and the water cooling system that can protect rubber packing from heat damage. Finally, the Mayer hardness was determined by the Vickers hardness tester and the surface roughness was measured by Se-4A surface roundness measuring instrument.

II-2. Experiment method

The samples that used in this experiment are the depleted UO_2 pellets that made of metalic ceramic form. The UO2 sample is originally prepared in the form of 12mm diameter and 16mm height cylinder dished at both uper and lower sides. The dished parts are removed each side about 1mm depth for the purpose of this experiment. The UO_2 samples are drilled by 5mm depth at four points to install the thermocouples. Also Zircaloy-2 samples are made with the same method. The experiment procedure is as follows;

1) calibrate the thermocouples and presser.
2) measure the surface roughness of the samples.
3) install the UO_2 pellet and zircaloy-2 within the test channel.
4) turn on the power of heaters, and wait untill the vacuum condition is about 0.1-0.3 torr with operating the water cooling system and the vacuum pump.
5) measure temperatures after thermal equilibrium with varying the contact pressure.
6) measure the sample surface roughness again after measurements are finished.
7) change the sample surface roughness with sand paper, and repeat the process from 2) to 6).

III. Results and Discussion

III-1. Data Calculation

The measured data are listed in table 1. Table 1 now the calcualtion of the thermal contact conductance from those data has been performed using Fourier's law and Newton's law of cooling as,

Table 1. Experimental Measures of Thermal Contact Conductance

Out-of-Pile-Experiment (In Vacuum)					
Case-Run	Materials	Surface Parameter Fuel Rs (μin)	Surface Parameter Cladding Rs (μin)	P (psi)	Hs Btu (h ft² °F)
1-1	UO_2-Zr-2	29.5	35.4	2080	434
2	UO_2-Zr-2	29.5	35.4	2740	524
3	UO_2-Zr-2	29.5	35.4	3390	570
4	UO_2-Zr-2	29.5	35.4	4050	612
2-1	UO_2-Zr-2	45.3	19.7	2080	367
2	UO_2-Zr-2	45.3	19.7	2740	430
3	UO_2-Zr-2	45.3	19.7	3390	465
4	UO_2-Zr-2	45.3	19.7	4050	499
3-1	UO_2-Zr-2	53.2	31.5	2080	244
2	UO_2-Zr-2	53.2	31.5	2740	314
3	UO_2-Zr-2	53.2	31.5	3390	364
4	UO_2-Zr-2	53.2	31.5	4050	410
4-1	UO_2-Zr-2	29.5	98.4	2080	234
2	UO_2-Zr-2	29.5	98.4	2740	274
3	UO_2-Zr-2	29.5	98.4	3390	296
4	UO_2-Zr-2	29.5	98.4	4050	324

Rs: Surface roughness,
Hs: Thermal contact conductance.

$$Q'' = K\frac{\Delta T}{\Delta X}, \quad (1)$$

$$Q'' = Hs\ \Delta T. \quad (2)$$

Where,

Q''; heat flux

ΔT; temperature difference between thermocouples.

ΔX; distance difference between thermocouples.

K ; thermal conductivity.

Hs ; thermal contact conductance.

The temperature dependent thermal conductivities for UO_2 and Zr-2[4, 5, 6] are written as,

$$K_f = \frac{3978.1}{(692.6+T)} + (6.02\times10^{-12})(T+460). \quad (3)$$

$$Kz = 7.15 + (2.47\times10^{-3})T + (1.67\times10^{-6})T - (3.33\times10^{-10})T. \quad (4)$$

where the unit is Btu/(hr-ft-°F) and the subscripts, f and z, are represented UO_2 and Zr-2 respectively. Using the equations (1), (2), (3), (4), we can get the surface temperature of sample by the extrapolation, and the thermal contact conductance is written as,

$$Hs = \frac{Q''}{T_{f,s} - T_{z,s}} \quad (5)$$

where $T_{f,s}$ and $T_{z,s}$ are fuel and cladding contact surface temperatures extrapolated from the measured value. The trend of the thermal contact conductance calculated finally by Eq. (5) is found to have the near same trend shown in fitting the data in the Ross & Stoute model.[7] Thus we have obtained the experimental correlation by teh form of Ross & Stoute correlation using the least square method. The correlation is written as,

$$Hs = \frac{Km\ P}{0.128\sqrt{Rs}\ Hm} + 119\ [\mathrm{Btu/(hr\ ft^2 °F)}]. \quad (6)$$

where P; contact pressure (psia).

$$Km = \frac{2K_f\ Kz}{K_f + Kz}$$

Hm; Mayer hardness of the cladding (psia.)

$Rs = (R_f^3 + Rz^2)/2$ (μft.)

R_f,Rz; fuel and cladding surface roughness.

III-2. Parameters effects

(1) Pressure effect

The thermal contact conductance depends on the pressure or local compressive stress, which acts to increase the area of contact by plastic deformation of the softer material by the harder one.[8] The majority of the heat flux may flow through these spots. The increase of pressure on UO_2 pellet can produce the more heat transfer from UO_2 pellet to Zr-2 cladding because the interface of two materials contacts more closely. In this experiments, the thermal contact conductance are measured under pressure changes from 2000 to 4000 psia. The resultant thermal contact conductances are shown in Figure 3 according to the pressure change keeping the surface roughness constant. As shown in the figure, the thermal contact conductance increases linearly with the change of pressure. The comparision of the thermal contact conductance fitted with our correlation and widely-used Ross & Stoute model is shown in Figure 4. The increasing rate of the thermal contact conducatnce in our correlation

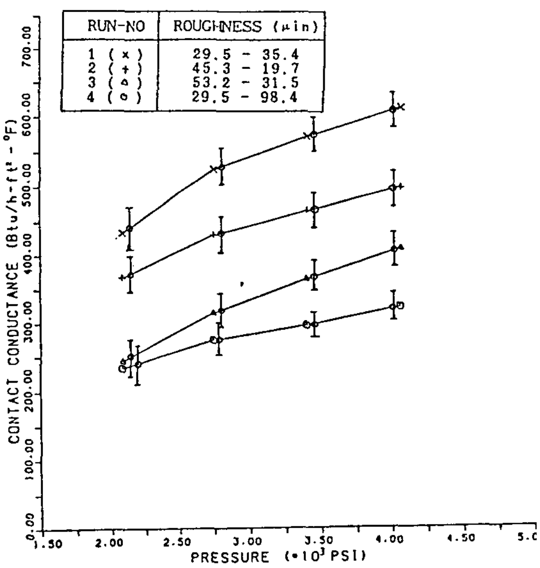

Fig. 3. Experimental Value of Contact Pressure vs. Contact Conductance in Vacuum

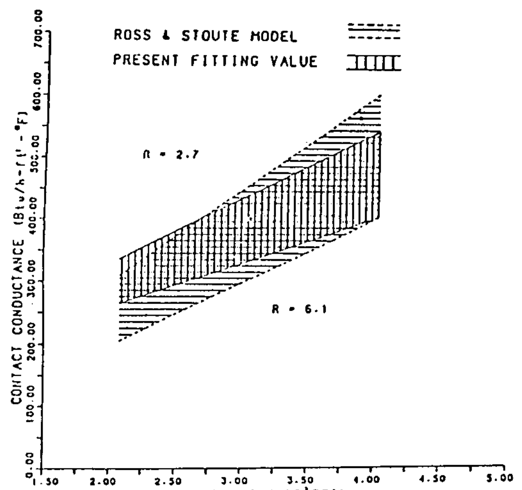

Fig. 4. Comparison of Presented Fitting Value and Ross & Stoute Model About P-Hs Graph

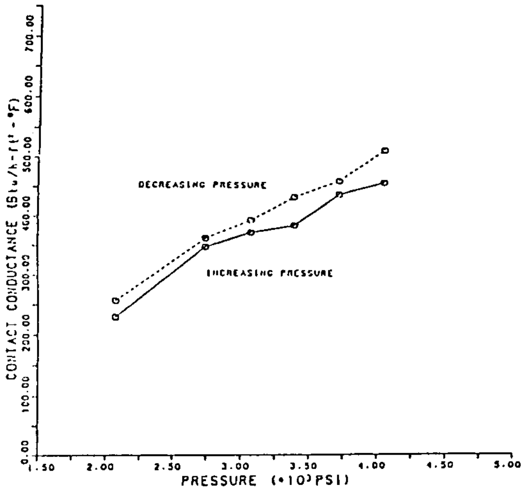

Fig. 5. Comparison of Increasing Pressure and Decreasing Pressure in Vacuum

Ross and Stoute model at high pressure and larger at low pressure. Also experiments have been performed with increasing pressure and decreasing pressure. As shown in figure 5, the former results are less than the later due to the plastic effect.

(2) Surface roughness effect

The heat transfer through the contact surface is greatly affected by surface condition between contacting materials. If the contacting material surfaces are smooth, the heat transfer would be increased due to the larger contact surface. However, if contact material surfaces are rough, the heat transfer would be decreased due to the smaller contact surface. In this experiment, the thermal contact conductances are measured by changing surface roughness from 2.7 to 6.1 μft. At the various pressure the results are shown in Figure 6. Also the comparison with the results from Ross & Stoute model is shown in Figure 7. The increasing rate of the thermal contact conductance according to reducing the roughness in our correlation is less than in Ross & Stoute model. The other parameter which is important to determine thermal contact conductane is Zr-2 Mayer hardness. The Mayer hardness depends on the Zr-2 surface temperature. The thermal contact conductance is known to be increased with decreasing Zr-2 Mayer hardness and the Mayer hardness decreases with increasing the surface temperature.[6] However, this experiment is carried out at nearly constant surface temperature about 300°F and thus the constant Mayer hardness is used through all experiments. Finally, the comparison of predicted values by the thermal

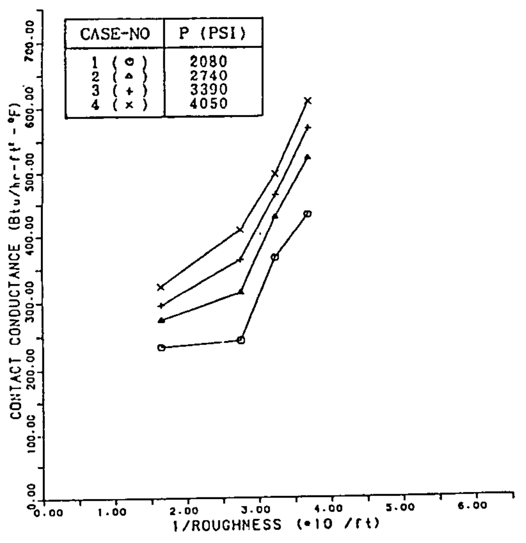

Fig. 6. Experimental Value of Roughness vs. Contact Conductance in Vacuum

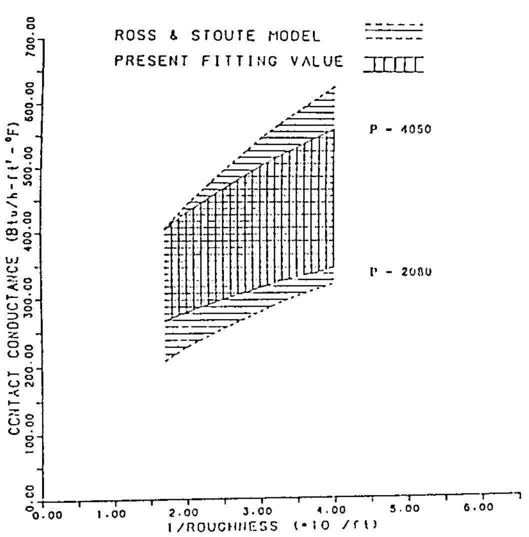

Fig. 7. Comparison of Presented Fitting Value and Ross & Stoute Model about Rs-Hs Graph

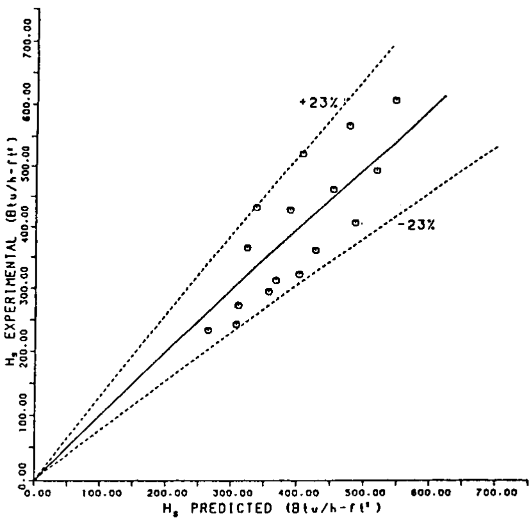

Fig. 8. Comparison of Predicted models and experimental data in vacuum

contact conductance correlation of Eq.(6) and measured values in shown in Figure 8. The dashed lines in the figure represents ±23% uncertainty in the experimental data.

IV. Conclusion

The experiments are carried out at various condition for the purpose of obtaining the fuel rod temperature distribution. The conclusions are that;

1) the thermal contact conducatance is proportional to the contact pressure between UO_2 pellet and Zr-2 cladding.
2) the thermal contact conductances measured by reducing pressure show more large value than that by increasing pressure.
3) the thermal contact conductance is root-inversely propotional to surface roughness between UO_2 pellet and Zr-2.
4) the experimental correlation is finally obtained in the form of Ross & Stoute model as,

$$Hs = \frac{Km\ P}{0.128\ Rs\ Hm} + 119\ [Btu/(hr\ ft^2{}^\circ F)].$$

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