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Sensitivity Analysis of Gap Conductance Models in Open Gap for PWR Fuel Performance Code, MERCURY

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1. Introduction

In the fuel performance code, the heat transfer occurring in the gap between the nuclear fuel pellet and the cladding is expressed as gap conductance. A base model for gap conductance is incorporated into the accident condition nuclear fuel performance code MERCURY, which is being developed by KAERI [1]. To evaluate the impact of gap conductance in the MERCURY code, it is necessary to conduct a sensitivity analysis of related models in addition to the basic model. This paper presents the results of an analysis of gap conductance models, particularly under open gap conditions where contact does not occur, as well as a sensitivity analysis of the input parameters.

2. Gap Conductance Model

The heat transfer through the gap between pellet and cladding is quantified by the gap conductance. The heat transfer mechanisms within the gap can be expressed the combination of heat transfer due to the gas present in the gap, heat transfer resulting from contact between the pellet and the cladding, and radiative heat transfer between the two surfaces.

The following expression is then utilized as a representative formulation for gap gas conductance in an open gap [2]:

$$h_{gap} = \frac{k_g}{d_g + C_r(\xi_1 + \xi_2) + (g_1 + g_2)}$$

where,

k_g = the thermal conductivity of mixed gas in gap,

d_g = the gap size that is computed in the mechanics solution,

C_r = the roughness coefficient,

ξ_1, ξ_2: the surface roughness of solid body 1, 2,

g_1, g_2: the temperature jump distance.

To predict gap conductance in an open gap, the models of the thermal conductivity of pure gases, the temperature jump distance, and the accommodation coefficient model are evaluated. The evaluated models are summarized in Table 1.

To evaluate the predictive performance of gap conductance based on combinations of model options, the model combinations were applied to the 11 experimental data sets presented by Garnier et al. [8]. The results of the Mean Absolute Percentage Error (MAPE) assessment are shown in Figure 1. While the combination of 1-1-1 shows the lowest value among the model combinations, the differences among all combinations remain within 10%.

Table 1. Model options included in gap conductance for open gaps.

Parameter	ID	Reference
Thermal conductivity of gas	1	Luscher [3]
	2	MATPRO [4]
	3	Lassmann [5]
Temperature jump distance	1	Kennard [6]
	2	Toptan [7]
Accommodation coefficient	1	Lanning [6]
	2	Toptan [7]

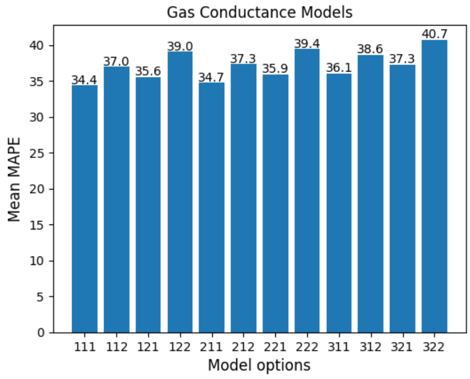


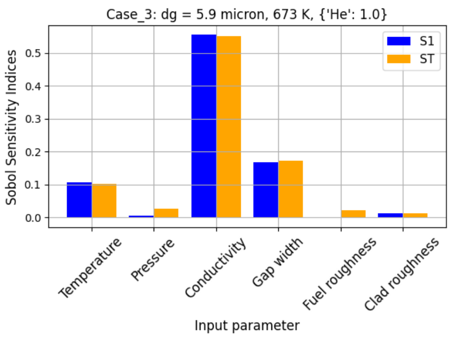
Fig. 1 Comparison of loss functions for gas conductance based on different models.

3. Sensitivity Analysis

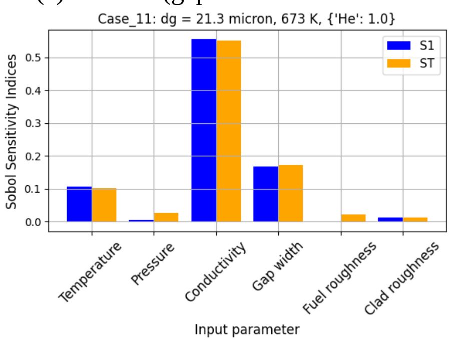
Sobol sensitivity analysis is a form of global sensitivity analysis that is particularly useful for nonlinear models. This type of analysis allows for the evaluation of the importance of input variables. For the sensitivity analysis of gas thermal conductivity, the model combination of 1-1-1, which exhibited the lowest MAPE value, was utilized. The input parameters selected for the sensitivity analysis included the thermal conductivity of pure gases, the pressure and temperature in the temperature jump distance model, roughness, and the gap thickness between the two specimens. The sensitivity analysis was conducted at a temperature of 673 K with a gap of 5.9 and 21.3 microns for helium (He) at a concentration of 1.0, as well as for the mixed gas composition of He=0.89 and Ar=0.11 with a gap of 5.9

microns at 287 K. An uncertainty range of 10% was uniformly applied to all input parameters.

The results of the Sobol sensitivity analysis are presented in Figure 2, which displays the outcomes for two conditions with different gap thicknesses at high temperatures among the experimental cases. Under the current calculation conditions, where the same uncertainty range is applied, the parameter that has the most significant impact on the output gas gap conductance is the thermal conductivity of the gas, followed by temperature and gap size. This trend is similarly observed across all 11 cases. This indicates that, to enhance the accuracy of gas conductance predictions, the precision of the thermal conductivity model for the gas is crucial among these key input parameters. If the uncertainty ranges for each parameter can be specified, the ranking of the key parameters may change. In the Sobol analysis, the first-order sensitivity index (S1) represents the main effect of the input parameters, while the total sensitivity index (ST) accounts for both the main effects and interactions with other input parameters. Therefore, a significant difference between S1 and ST values suggests that the corresponding input parameter has considerable interactions with other factors. The relatively small difference between these two values in the current sensitivity analysis results indicates that there is minimal interaction among the input parameters.



(a) Case 3 (gap thickness = 5.9 micron)



(b) Case 11 (gap thickness = 21.3 micron)

Fig. 2 Sobol sensitivity analysis results for gap gas conductance

3. Conclusions

An analysis of model options for the gap conductance model was conducted to expand the options of the MERCURY code. Sensitivity analysis was performed on the models included in gap gas conductance, specifically the thermal conductivity models for pure gases, the accommodation coefficient model, and the temperature jump distance model. It was confirmed that the differences based on the pure gas thermal conductivity models remained within 10%. However, this difference does not indicate a discrepancy between the actual thermal conductivity and the predictive models. A Sobol sensitivity analysis, a global sensitivity analysis method, was conducted, confirming that the thermal conductivity of the gas has the most significant impact on the predictive performance of the overall model. Additionally, the relatively small difference between the first-order sensitivity index (S1) and the total sensitivity index (ST) values indicates minimal interaction among the input parameters, suggesting that the effects of individual parameters on the output are largely independent.

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