PRESSURE TUBE-CALANDRIA TUBE THERMAL CONTACT CONDUCTANCE

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Abstract

A critical review of publications concerning thermal contact conductance between two conforming microscopically rough surfaces is described. Various existing models, developed for different applications, such as the Ross-Stout model are examined. An outline for the development of a new contact conductance model is established. The new model will focus on contact conductance between the pressure tube and calandria tube of a CANDU reactor under a pressure tube deformation event resulting in mechanical contact between the two tubes. The methodology of model development for the interaction between randomly rough surfaces under transient contact pressure for this specific application is described.

Introduction

In a CANDU reactor conditions exist, such as a large break LOCA, in which an overheated pressure tube can deform and come into contact with its surrounding calandria tube. Under these circumstances a pathway is created for heat to travel between the hot pressure tube and the moderator. This is undesirable and poses a threat to fuel channel integrity. If contact conductance between the pressure tube and calandria tube is sufficiently high, calandria tube dryout may occur, leaving the calandria tube susceptible to damage.

Mechanistic modeling of the PT-CT heat transfer coefficient in this transient case is a necessary step for assurance of fuel channel integrity in the safety analysis of critical break large LOCA. The goal of this paper is to outline the processes involved in heat conduction between the calandria tube and pressure tube in a CANDU reactor. Also, an outline for methodology in mechanistic model development is presented.

Review of Existing Contact Conductance Models

In real world applications machined surfaces are not perfectly smooth; they have some degree of roughness. This complicates the issue of heat transfer between two surfaces. When two microscopically rough surfaces come into contact with each other, the asperities of each surface will cause areas of contact and gaps between the two contacting materials. The conductance from one material to the other can be represented as the sum of conductance through the gap regions and solid contact regions. This section is a review of selected gap conductance models which have been reported in literature.

Ross and Stoute

The Ross-Stoute model (1962) was developed for contact conductance between fuel pellet and sheath. It is one of the most widely used models in nuclear fuel computer codes. The total conductance is given as the sum of the conductance across contact points and the conductance across the gas gap.

$$h = h_{cont.} + h_{gas}$$

The conductances of the contact and gap areas are given by the following relationships:

$$h_{cont} = \frac{k_s P_c}{C\sqrt{\sigma^*}H}, h_{gas} = \frac{2k_g}{\sigma_1 + \sigma_2}$$

Where k_s is the harmonic mean conductivity of the materials
k_g is the gas gap conductivity
P_c is the contact pressure at the interface
H is the bulk microhardness
σ^* is the mean square of the materials surface roughness
σ_1, σ_2 are the effective roughness of each material
C is an empirical constant

Shlykov and Ganin

The Shlykov-Ganin model (1963) is developed under the assumption that the thermal resistances between the contact areas and gas gap areas can be summed like parallel resistors:

$$\frac{1}{R} = \frac{1}{R_{cont.}} + \frac{1}{R_{gas}}$$

Note that h = 1/R

The thermal resistance across the gas gap is treated in a similar way to the Ross-Stoute model. It is assumed that there is no convection, therefore the conductance through the gap is modeled using the gas conductivity and a gas gap thickness estimate based on the material roughness.

The contact resistance is developed assuming that each contact point has the same area. Increasing the contact pressure only increases the number of contact points and not the individual contact area. Resistances of each contact site are summed as parallel resistances. This gives the relationship:

$$R_{cont.} = \frac{3\sigma_b S}{2.1 N \lambda_M} \times 10^{-4}$$

Where σ_b is the ultimate material strength
λ_M is the thermal conductance of the metal
N is the normal surface loading
S is the nominal contact area

Yovanovich

Yovanovich et al. (1987) compares the preceding methods against data and develops an iterative algorithm for contact conductance in compound tubes using a new correlation.

Yovanovich model:

$$h_{cont.} = 1.25 \frac{k_s m}{\sigma} \left(\frac{P_c}{H_e} \right)^{0.95}, h_{gas} = \frac{k_g}{Y + \alpha_a \beta \Lambda}$$

Where m is the effective absolute surface slope
H_e is the effective microhardness
α_a is the accommodation parameter
β is the fluid parameter
Λ is the molecular mean free path
Y is the mean plane separation

The model includes the addition of empirically determined terms. The gas gap conductivity now takes gas temperature and molecular movement into account.

The iterative algorithm developed by Yovanovich involves using a guessed contact pressure to calculate a contact conductance. The calculated conductance is used to determine radial stress in the inner and outer sections of the compound cylinder. A new contact pressure is determined and the procedure is repeated until convergence.

Event Progression

Pressure tube-Calandria tube contact is a transient process. The stages involved in this event can be broken down into the Initial Contact phase and the Post Contact phase. Each has a different set of governing phenomena.

Initial Contact Phase

When fuel cooling ability is lost, the overheating pressure tube will undergo plastic deformation until contact with the calandria tube is made. Initially, the temperature difference between the two tubes is large. This combined with an expected high contact pressure, will result in a high initial heat transfer coefficient at the PT-CT interface. Heat is transferred to the calandria tube causing its temperature to rise. The rising temperature of the calandria tube (which initially can be assumed to be at the same temperature as the moderator) causes heat transfer from the calandria tube to the moderator. Heat transfer between the calandria tube and moderator is highly dependant on the conditions existing at the moderator-calandria tube interface and is not outlined in this paper. The temperature change in the calandria and pressure tubes can be expressed as a set of coupled differential equations given in [5].

Post Contact Phase

The initially high temperature difference and contact conductance between the two tubes will cause a rapid temperature reduction due to transfer of stored heat in the pressure tube. As the temperature of the pressure tube decreases and the temperature of the calandria tube increases, thermal contraction of the pressure tube and expansion of the calandria tube will decrease the contact pressure at the PT-CT interface. From the models outlined above, it can be seen that PT-CT conductance decreases after initial contact due to a decrease in contact pressure. The goal is to study governing phenomena involved and determine the rate of contact conductance reduction.

Methodology:

There are two linked phenomena which must be explored in the PT-CT contact conductance transient:

1. Contact conductance as a function of contact pressure between the two tubes
2. The relationship between temperature, radial stress and contact pressure

To obtain a relationship for contact conductance as a function of pressure for zircaloy pressure and calandria tubes the methodology in the models developed above will be reviewed. All assumptions will be verified or changed according to the specific materials involved in this system. Experimental data will be used to develop new empirical values.

Factors involved in PT-CT thermal contact resistance:

- Area of Contact, Gas Gap Thickness, Surface Deformation
    -> Surface Characteristics (Roughness, Hardness)
-Contact Pressure
    -> Radial Stress
-Temperature
    -> Thermal Creep Strain, Elastic Thermal Expansion/Contraction

The relationships between the phenomena involved will result in a coupled set of equations and correlations. An iterative algorithm will be implemented to solve the equation set.

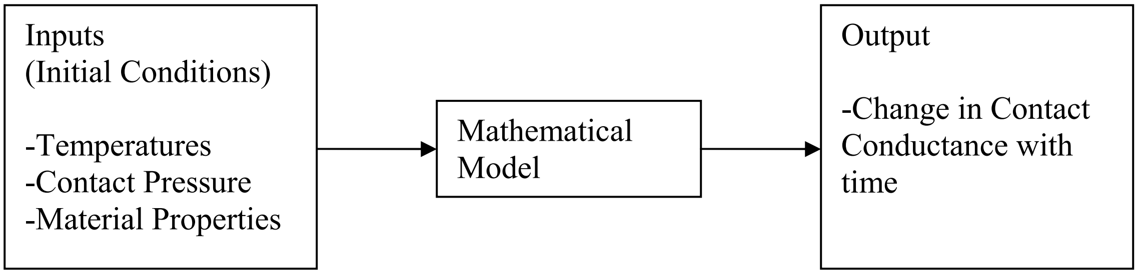

Figure 1: Flow chart illustrating inputs and outputs of required model.

Following completion and verification testing of the model a validation exercise will be conducted using available experimental data. At this time the availability of data has not yet been confirmed.

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