Flow Pattern Modeling of Thermal-hydraulic Analysis Tool for CANDU Fuel Channel

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1. Introduction

A loss of pressure tube geometric integrity due to a break (hole or a long crack) can result in loss or degradation of fuel cooling both in the vicinity of the crack and downstream of it. It will also cause pressurization of the otherwise unpressurized annular space between the pressure and calandria tube and discharge of the fluid through end fitting bearing clearances. Depending upon the mechanisms that lead to the loss of pressure tube integrity and the mechanical and hydraulic loads on the calandria tube, a simultaneous loss of calandria tube integrity is possible but not inevitable. If the calandria tube also fails by rupture, the net discharge from the fuel channel is limited by the break size. When the calandria tube survives pressurization after a pressure tube break, estimates of flow redistributions within the fuel channel due to a crack in the pressure tube are required for fuel and channel integrity assessments. In this case the net discharge through the fuel channel is limited by the lower of the break discharge capacity and the capacity of the flow discharge through the clearance between the end fitting bearings. When the fluid flow through the end fitting bearings pressurizes the bellows enough to fail one of both bellow, the loss of net fluid flow through the channel combines with bypass of the fluid around the innards of the fuel bundles to create complex flow patterns that result in certain segments of the fuel channels both under and downstream of the crack to experience deterioration of cooling and a reduction of margins to dry-out.

PT-CRACK, which is a thermal-hydraulic analysis tool for CANDU fuel channel, has been developed in order to assess the complex TH phenomena considering the pressure tube crack while calandria tube remains intact. Reference [1] describes the modeling background of the PT-CRACK code. This paper explains the flow pattern modeling methodology in detail of PT-CRACK and also shows the preliminary analysis results for dry-out margin with the consideration of pressure tube enlargement and feeder thinning.

2. Flow Pattern Modeling

PT-CRACK is a two phase homogeneous steady state thermal hydraulic network code. It uses linear theory to set up the conservation equations and uses a sparse matrix routine to solve the many hundred mass, momentum and energy conservation equations setup for a series of interconnected flow loops and junctions that represent the possible flow paths in axial and radial direction both upstream of the pressure tube crack and downstream of the crack.

All the flow paths represented by a series of networks connected to one another as illustrated in Fig. 1. The crack region can be divided into up to 99 axial parts.

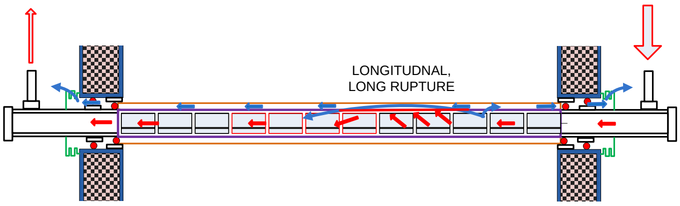

Fig. 1. Flow patterns after a pressure tube longitudinal crack.

Each network is composed of nodes and links as shown in Fig. 2. Fluid properties are calculated at nodes. Nodes represent supply volumes as well and flow junctions. One end node for a link is called the upstream node and the flow is positive when it occurs from upstream to the downstream node. Links represent parts of feeders, end fittings, fuel sub-channels, pressure tube sub-channels and annulus sub-channels. Each of these is connected to two or more nodes. Fig. 3 illustrates the cross section of flow paths at any channel.

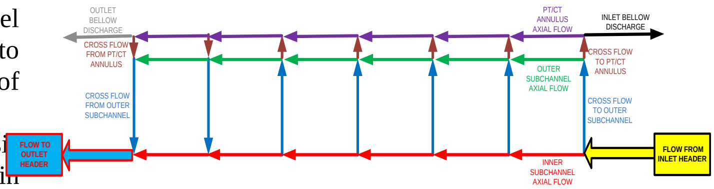

Fig. 2. Axial and cross flow network development.

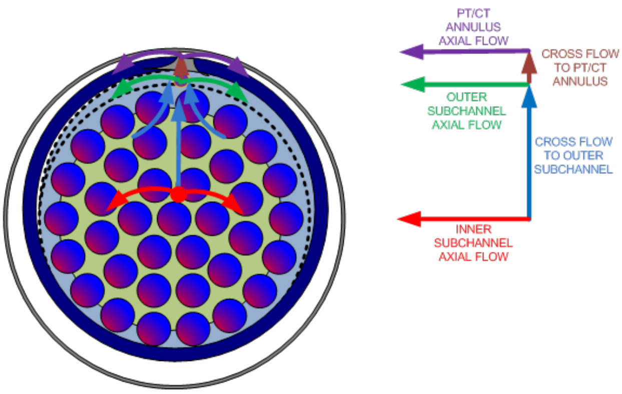

Fig. 3. Flow paths at any channel cross section under crack.

The equations for the conservation of mass and energy are used to iterate the pressure and enthalpy at the junction. The mass flow rate and the enthalpy exiting node are those entering the segments attached to them and the same parameters exiting the segments are inlet values for the junction volumes. Nodal contents are taken to be homogeneously distributed and an average nodal pressure is defined. The link pressure, and corresponding saturation properties are calculated based upon the pressure of the donor node. A link averaged flow rate is used for mass, momentum and energy interchange.

The broken part of the pressure tube contains the main network. It is divided into N linear 'parts'. For each 'part', three axial links form two interconnected loops composed of 3 axial nodes unique to it and 4 radial interconnects shared with adjoining loops. An outer loop is fanned by the headers. There are 2N+1 loops, 5N+4 links, 3N+3 junctions including 4 junctions with specified boundary conditions as shown in Fig. 4.

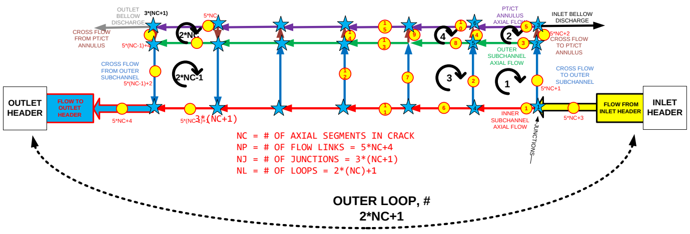

Fig. 4. Flow network used in PT-CRACK code.

The two outer links formed between the headers and the beginning of the pressure tube crack is composed of 10 feeder segments, 2 end fitting links and the specified number of bundles in the intact part of the pressure tube on either end. It is treated in the evaluation of the pressure drop of the outer loop as one pseudo link. The pressure drop in each of these 'pseudo-links' is mostly a function of the geometry of the feeders of the specified channel and is evaluated separately.

Flow and fluid properties at each end of each link must be determined. The mass conservation equations are linear in link flows, while the momentum equations are non-linear. The energy equations are also linear. If the momentum equations can be made linear in link flows then any conventional method of solving simultaneous linear equations may be used. Linear theory is used to transform each term of the pressure drop equation. The whole set of simultaneous equations is solved in two groups of mass-momentum network equations and nodal energy equations coupled at each iteration step. The solution procedure is therefore iterative and requires several solutions of a set of simultaneous linear equations.

The solution to the large number of equations is achieved by a sparse matrix solution program. Single phase frictional pressure drop includes the minor loss term by the definition of an equivalent flow length. The two phase frictional pressure drop is correlated by externally specified choice of homogeneous two-phase multiplier or Martinelli-Nelson two phase multiplier.

Headers are the pressure and enthalpy boundary conditions and the end fittings are flow boundary conditions that vary with the local fluid conditions. The latter are literally elastic boundary conditions.

3. Preliminary Analysis Results from PT-CRACK

Fuel channel TH analysis was done by using the developed PT-CRACK with the consideration of pressure tube creep and feeder thinning under the pressure tube crack condition.

Fig. 5 and 6 show the results of flow increase in the case of only feeder thinning and only PT creep, respectively. When only feeder thinning was assumed, much increase of inlet flow were detected at lower power channels (Fig. 5) and in the case of PT creep only high power channels showed much increase of inlet flow (Fig. 6). Fig. 7 is the results of channel flow increase when both feeder thinning and PT creep were assumed together and we can check that all channels show almost uniform flow increase because of the compensation of feeder thinning and PT creep at each region of lower and high power region.

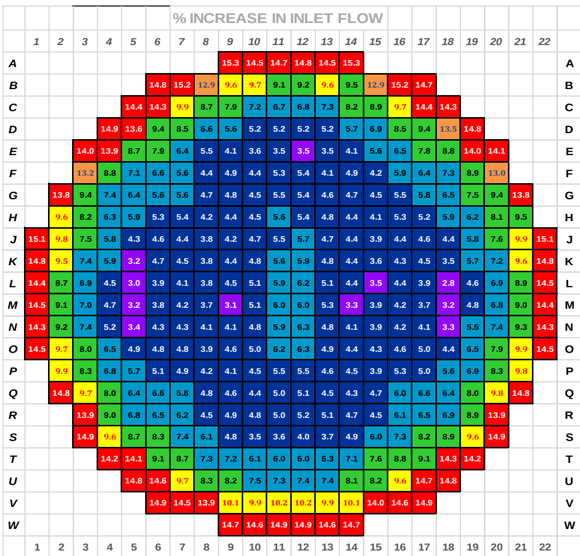

Fig. 5. Effect of feeder thinning on inlet flow.

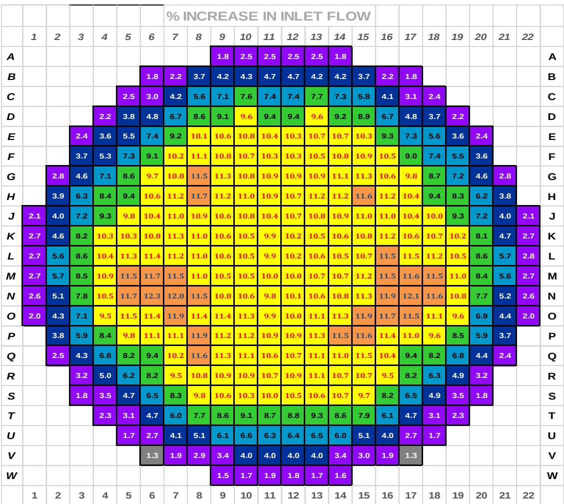

Fig. 6. Effect of pressure tube creep on inlet flow.

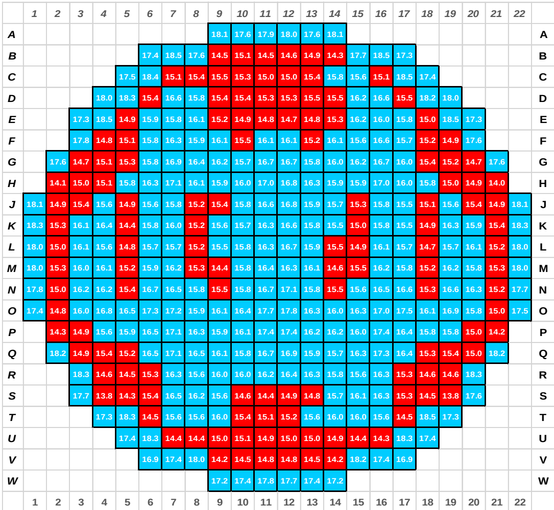

Fig. 7. Effect of feeder thinning and PT creep on flow.

When we assumed a 3 m central crack with 5 mm width in the pressure tube, a dry-out occurred at all outer channels (low power channels) and some central channels (high power channels) and Fig. 8 shows the calculated dry-out length for each channel and Fig. 9 is the peak fuel centerline temperature.

Through these analysis results, we confirmed the availability of PT-CRACK code and will apply it for CCP calculation in order to assess the operational safety margin.

5. Conclusions

This paper describes the technical methodology how to make the flow pattern modeling to develop PT-CRACK which is the TH analysis tool for CANDU fuel channel considering the pressure tube crack with calandria tube intact. Through the preliminary TH analysis with the consideration of PT crack, we confirmed the availability of PT-CRACK code and we will apply it for CCP calculation in order to assess the operational safety margin for currently operating CANDU reactor.

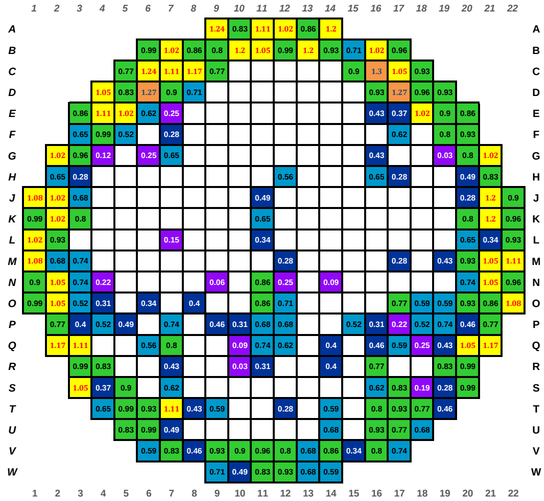

Fig. 8. Dry-out length for 3m long and 5 mm wide PT crack.

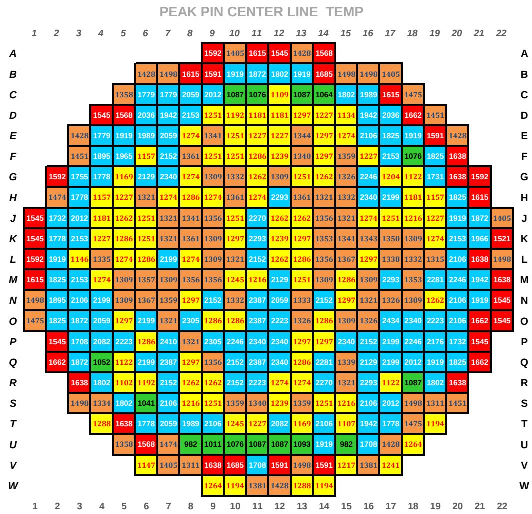

Fig. 9. Peak fuel centerline temperature for crack.

Acknowledgments

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[1] J.Y. Jung, E.H. Ryu and S. Nijhawan, Modeling background for thermal-hydraulic analysis tool of CANDU fuel channel, Proceedings of the 2020 KNS Conference, Changwon, Oct. 22 – 23, 2020.