Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 1995

Calculation of Equivalent Feeder Geometries for CANDU Transient Simulations

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Abstract

This paper describes a methodology for determination of representative CANDU feeder geometry and the pressure drops between inlet/outlet header and fuel channel in the primary loop. A code, MEDOC, was developed based on this methodology and helps perform a calculation of equivalent feeder geometry for a selected channel group on the basis of feeder geometry data (fluid volume, mass flow rate, loss factor) and given property data (pressure, quality, density) at inlet/outlet header. The equivalent feeder geometry calculated based on this methodology will be useful for the transient thermohydraulic analysis of the primary heat transport system for the CANDU heavy water-cooled pressure tube reactor.

1. Introduction

The CANDU-6 reactor consists of 380 fuel channels with corresponding inlet and outlet feeders connected to the inlet and outlet headers. Transient thermohydraulic analysis of this geometry ideally requires that each channel and associated inlet/outlet feeder should be modelled. However, for engineering simulator purposes, it is neither practical nor necessary to model each individual channel, as several channels may be grouped together due to their similar powers, flows, elevation, etc.. The challenge is to find an appropriate number of channel groups with representative inlet/outlet feeder geometry for each group.

This paper presents a methodology for the calculation of representative feeder geometries for a grouping of channels, and presents some sample results for a CANDU-6 core. The emphasis is on the methodology rather than on any particular correlation employed, or on the individual results obtained.

In order to obtain representative feeder geometry, certain criteria are used for guidance. These include the need to have representative fluid volumes, feeder resistance or pressure drop, and channel elevation. A starting point is to group adjacent channels on the basis of similar channel power and flow. Since some adjacent channels may have quite different feeder geometries, the initial grouping of channel needs to be examined for any large

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deviations of feeder pressure drop, fluid volume, etc. from the average for the group. This may require the transfer of such channels to another group, or a regrouping of the channels themselves.

The pressure drop for each channel inlet and outlet feeder is obtained using a method similar to that in the NUCIRC [1] code, but with some simplifying assumptions. For this purpose, a code MEDOC (Methodology for Equivalent FeeDer GeOmetry Calculation) was developed as described below.

2. Selection of Channel Groups

The CANDU-6 core channels are divided into several groups based on channel power and flow. A selected channel power distribution is a time-average channel power using the 8-bundle shift fueling scheme shown in Wolsung Unit 3&4 PSAR of CANDU-6 [2]. Since the power distribution is symmetric, only half of 380 channels are considered and they are divided arbitrarily into 8 groups. The initial channel composition of each group is shown in Table 1. The low number group channels are located in the outer region of the core and the high number group channels are located in the inner region. The average values and standard deviations (%) of representative parameters of each group are shown in Table 2.

Table 1. Composition of Divided Channel Groups

Name of Group	Number of Channels	Composition of Channels
G1	24	A9,A10,A11,B6,B7,B8,B9,B10,B11,C5,C6,C7,D4,D5,E3,E4,F3,G2,G3,H2,J1,J2,K1,L1
G2	24	M1,N1,O1,O2,P2,Q2,Q3,R3,S3,S4,T4,T5,U5,U6,U7,V6,V7,V8,V9,V10,V11,W9,W10,W11
G3	28	C8,C9,C10,C11,D6,D7,D8,D9,D10,D11,E5,E6,E7,F4,F5,F6,G4,G5,G6,H3,H4,H5,J3,J4,K2,K3,L2,L3
G4	28	M2,M3,N2,N3,O3,O4,P3,P4,P5,Q4,Q5,Q6,R4,R5,R6,S5,S6,S7,T6,T7,T8,T9,T10,T11,U8,U9,U10,U11
G5	21	H6,J5,J6,K5,K6,K7,K8,K9,K10,K11,L9,L10,L11,M9,M10,M11,N9,N10,N11,O10,O11
G6	20	K4,L4,M4,N4,O5,P6,Q7,Q8,Q9,Q10,Q11,R7,R8,R9,R10,R11,S8,S9,S10,S11
G7	24	E8,E9,E10,E11,F7,F8,F9,F10,F11,G7,G8,G9,G10,G11,H7,H8,H9,H10,H11,J7,J8,J9,J10,J11
G8	21	L5,L6,L7,L8,M5,M6,M7,M8,N5,N6,N7,N8,O6,O7,O8,O9,P7,P8,P9,P10,P11

3. Calculation of Average Feeder Pressure Drop

In order to calculate the average feeder pressure drop for each channel group, pressure drop was first calculated for each channel feeder section, using an algorithm developed in the MEDOC code. The following simplifying assumptions were employed: 1) bends and elbows are located in the section near the header of the feeder; 2) pressure drop due to area change is considered in the section near the fuel channel of the feeder; 3) fluid density and viscosity are functions of temperature only; 4) pressure drop due to gravity is neglected.

Table 2. Average Values and Deviations of Representative Parameters of Each Group

Name of Group	Channel Power (kW) (±%)	Mass Flow Rate, $\bar{m}$ (kg/s) (±%)	Inlet Fluid Volume, $\overline{V_{in}}$ (m^3) ($x10^{-3}$) (±%)	Outlet Fluid Volume, $\overline{V_{out}}$ (m^3) ($x10^{-3}$) (±%)	Inlet Loss Factor, $\overline{K_{in}}$ (±%)	Outlet Loss Factor, $\overline{K_{out}}$ (±%)	Feeder Elevation (m) (±%)
G1	3724 (±13.0)	15.10 (±13.3)	10.89 (±26.5)	22.64 (±14.5)	0.34 (±13.1)	1.59 (±10.0)	3.80 (±12.7)
G2	3603 (±15.3)	14.84 (±13.5)	20.27 (±27.3)	42.33 (±8.4)	0.62 (±12.3)	2.52 (±5.5)	3.57 (±15.1)
G3	5431 (±8.9)	22.67 (±11.4)	16.19 (±3.7)	33.60 (±13.7)	0.31 (±3.9)	1.45 (±7.2)	5.48 (±8.5)
G4	5383 (±9.9)	22.49 (±10.0)	27.30 (±8.0)	63.22 (±16.4)	0.50 (±2.0)	2.03 (±6.3)	5.39 (±9.9)
G5	6363 (±1.3)	26.83 (±3.1)	26.42 (±22.6)	58.20 (±15.9)	0.37 (±6.8)	1.58 (±7.1)	6.33 (±1.4)
G6	6374 (±1.5)	26.65 (±2.9)	34.89 (±10.7)	76.64 (±6.4)	0.45 (±5.5)	1.84 (±5.9)	6.40 (±1.5)
G7	6397 (±0.9)	27.05 (±2.6)	19.59 (±12.0)	43.47 (±6.6)	0.29 (±4.3)	1.35 (±3.7)	6.34 (±0.9)
G8	6546 (±0.6)	27.42 (±2.2)	33.37 (±3.6)	70.44 (±4.0)	0.39 (±3.5)	1.69 (±2.8)	6.57 (±1.0)

3.1 Inlet Header to E/F (Inlet Feeder)

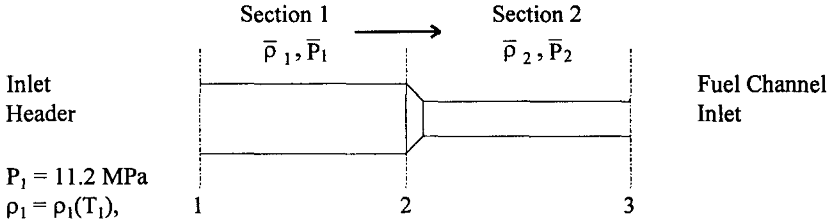

Fig. 1 *Configuration of Inlet Feeder*

Since the flow in a channel of the inlet feeder is liquid only, two-phase flow multiplier is assumed not to be considered in the inlet feeder. The total pressure drop ($\Delta P_{t,in}$) for each feeder section is mainly composed of frictional ($\Delta P_{f,in}$), acceleration ($\Delta P_{a,in}$) and area change ($\Delta P_{c,in}$) pressure drop, neglecting gravitational pressure drop, as follows:

$$\Delta P_{t,in} = \Delta P_{f,in} + \Delta P_{a,in} + \Delta P_{c,in} \qquad [Pa] \qquad (1)$$

where

$$\Delta P_{f,in} = \frac{1}{2}\bar{\rho}\left(\frac{4\dot{m}}{\pi\,\bar{\rho}\,D^2}\right)^2\left[f\frac{L}{D} + K\right] \qquad (2)$$

$$\Delta P_{a,in} = \left(\frac{4\dot{m}}{\pi\,D^2}\right)^2 [1/\rho_e - 1/\rho_i] \qquad (3)$$

$$\Delta P_{c,in} = \frac{1}{2}\bar{\rho}\left(\frac{4\dot{m}}{\pi\,\bar{\rho}}\right)^2\left[\frac{1}{D_2^4} - \frac{1}{D_1^4}\right] \qquad (4)$$

where ρ_e and ρ_i are the density at exit and inlet position of each section of the feeder, and subscript 1 and 2 means section 1 and 2 of the inlet feeder (see Fig. 1). The pressure drop in the bends and elbows is included in the frictional pressure drop through the loss factor K. The friction factor, f, is evaluated using the Colebrook correlation [3] given by:

$$\frac{1}{\sqrt{f}} = -2\,\log\left(\frac{\varepsilon / D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad (5)$$

where ε is feeder roughness, D is feeder diameter and their units are [m], and Re is Reynolds number given by $Re = (4\,\dot{m})/(\pi\,\mu\,D)$.

In order to calculate total pressure drop of an inlet feeder, unknown pressures at position 2 and 3 (P_2 & P_3) are estimated based on the given inlet header pressure P_1, and a constant fluid density ρ_1 dependent only upon the inlet header temperature T_1. The average pressure drop in a group of channels of the inlet feeder is obtained as follows:

$$\overline{\Delta P_{t,in}} = \frac{1}{N}\sum_{i=1}^{N}\Delta P_{t,in}(i) \qquad [Pa] \qquad (6)$$

where $\Delta P_{t,in}(i)$ is the pressure drop in each inlet feeder.

3.2 Outlet Header to E/F (Outlet Feeder)

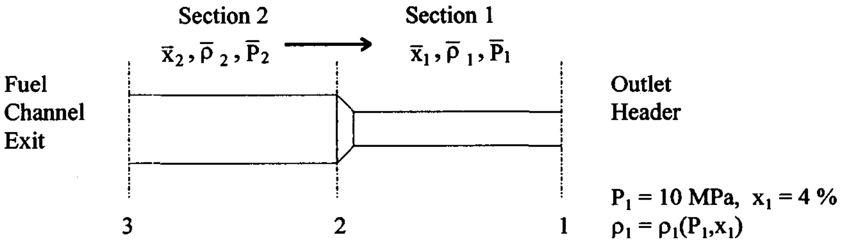

Fig. 2 Configuration of Outlet Feeder

Since the flow in the outlet feeder has some steam quality, a two-phase multiplier, ϕ^2, is used for pressure drop calculation. The total pressure drop ($\Delta P_{t,out}$) for one channel in the outlet feeder is mainly composed of frictional in straight pipe ($\Delta P_{f,out}$), frictional in bends and elbows ($\Delta P_{b,out}$), acceleration ($\Delta P_{a,out}$) and area change ($\Delta P_{c,out}$) pressure drop, neglecting gravitational pressure drop, as follows:

$$\Delta P_{t,out} = \Delta P_{f,out} + \Delta P_{b,out} + \Delta P_{a,out} + \Delta P_{c,out} \qquad [\mathrm{Pa}] \qquad (7)$$

where

$$\Delta P_{f,out} = \phi^2(\bar{x},\bar{P})\,\frac{1}{2}\bar{\rho}\left(\frac{4\dot{m}}{\pi\,\bar{\rho}\,D^2}\right)^2\left[f\frac{L}{D} + K\right] \qquad (8)$$

$$\Delta P_{b,out} = \phi_b^2(\bar{x},\bar{P})\,\frac{1}{2}\bar{\rho}\left(\frac{4\dot{m}}{\pi\,\bar{\rho}\,D^2}\right)^2 [K] \qquad (9)$$

$$\Delta P_{a,out} = \left(\frac{4\dot{m}}{\pi\,D^2}\right)^2\left[\left(\frac{x\rho_f + (1-x)\rho_g}{\rho_f\;\rho_g}\right)_e - \left(\frac{x\rho_f + (1-x)\rho_g}{\rho_f\;\rho_g}\right)_i\right] \qquad (10)$$

$$\Delta P_{c,out} = \frac{1}{2}\bar{\rho}\left(\frac{4\dot{m}}{\pi\,\bar{\rho}}\right)^2\left[\frac{1}{D_1^4} - \frac{1}{D_2^4}\right] \qquad (11)$$

where subscript e and i means exit and inlet position in each section of the outlet feeder, respectively (see Fig. 2). Note that in Eq. (9) since L/D for elbows and bends are unknown, it is assumed to be much less than K, i.e. L/D « K.

The two-phase flow multiplier for the outlet feeder is evaluated using the Fitzsimmons correlation [4] given by:

$$\phi^2(\bar{x},\bar{P}) = 1 + 0.65\,(\phi_{MN}^2(\bar{x},\bar{P}) - 1) \qquad (12)$$

where $\phi_{MN}^2(\bar{x},\bar{P})$ is the Martinelli-Nelson two-phase multiplier[1]. The two-phase pressure drop multipliers in bends and elbows for the outlet feeders are treated differently[1]:

$$\phi_b^2(\bar{x},\bar{P}) = C\,[\phi^2(\bar{x},\bar{P})]^n \qquad (13)$$

where C and n are constants depending on the elbow or bend geometry. Typical values of C and n are 1.07 and 1.27.

In order to calculate total pressure drop in the outlet feeder, unknown pressures and steam qualities at position 2 and 3 (P_2, P_3, x_2,x_3) are estimated iteratively, based on the pressure and quality (P_1,x_1) and the density $\rho_1(P_1,x_1)$ at the outlet header, assuming that enthalpy change in the outlet feeder is negligibly small. The average pressure drop in a group of channels of the outlet feeder is obtained as follows:

$$\overline{\Delta P_{t,out}} = \frac{1}{N}\sum_{i=1}^{N}\Delta P_{t,out}(i) \tag{14}$$

where $\Delta P_{t,out}(i)$ is the pressure drop in each outlet feeder.

4. Determination of Equivalent CANDU Feeder Geometry

The equivalent feeder geometries, i.e., a single equivalent diameter and length of the inlet and outlet feeders in each channel group are derived based on the average parameters given in Table 2 above, using the methodology described below:

4.1 Equivalent Inlet Feeder Diameter and Length (D_{in}, L_{in})

The pressure drop for a single equivalent diameter and length for each channel group is composed of frictional and acceleration pressure drop,

$$\overline{\Delta P_{t,in}} = \frac{1}{2}\bar{\rho}_{in}\left(\frac{4\,\bar{m}}{\pi\;\bar{\rho}_{in}D_{in}^{2}}\right)^{2}\left[f(D_{in})\frac{L_{in}}{D_{in}}+\overline{K_{in}}\right]+\left(\frac{4\,\bar{m}}{\pi\;D_{in}^{2}}\right)^{2}[1/\rho_3 - 1/\rho_1] \tag{15}$$

where the average density, $\bar{\rho}_{in} = (\rho_1+\rho_3)/2$, is estimated from the densities ρ_1 and ρ_3 at inlet header and fuel channel inlet, respectively (in this case a constant). The equivalent feeder length, L_{in}, can be eliminated using the fluid volume relation,

$$\overline{V_{in}} = \frac{\pi}{4}D_{in}^{2}\,L_{in} \tag{16}$$

giving an expression:

$$f(D_{in}) = C_1 D_{in}^{7} - C_2 D_{in}^{3} \tag{17}$$

where $C_1 = \overline{\Delta P_{t,in}}\;\pi^3\;\bar{\rho}_{in}/(\,32\;\bar{m}^2\;\overline{V_{in}}\,)$,

$C_2 = \pi\,(\,\overline{K_{in}} + 2\;\bar{\rho}_{in}\,[1/\rho_3 - 1/\rho_1]\,)\,/\,(4\;\overline{V_{in}}\,)$

Also, friction factor f is related implicitly to D_{in} from the Colebrook correlation[4]:

$$\frac{1}{\sqrt{f(D_{in})}} = -2\,\log\left(\frac{\varepsilon\;/\;D_{in}}{3.7} + \frac{2.51}{Re\,\sqrt{f(D_{in})}}\right) \tag{18}$$

where $Re = 4\;\bar{m}/(\pi\,\bar{\mu}\;D_{in})$, and $\bar{\mu} = (\mu_1+\mu_3)/2$. From above two equations, the two unknowns, namely, friction factor $f(D_{in})$ and equivalent diameter D_{in} are determined numerically. Finally, the equivalent length L_{in} was evaluated from Eq. (16).

4.2 Equivalent Outlet Feeder Diameter and Length (D_{out}, L_{out})

The single equivalent outlet feeder diameter and length for a channel group is determined by the same method as that used for calculation of the equivalent inlet feeder diameter and length. Using the following three equations for pressure drop, fluid volume and friction factor relations, the three unknown variables D_{out}, L_{out}, and $f(D_{out})$ can be evaluated:

$$\overline{\Delta P_{t,\,out}} = \phi^2(\overline{x},\overline{P})\ \overline{\rho}_{out} \left(\frac{4\,\overline{m}}{\pi\ \overline{\rho}_{out}\, D_{out}^2}\right)^2 \left[f(D_{out})\ \frac{L_{out}}{D_{out}} + \overline{K_{out}}\ \right]$$

$$+ \left(\frac{4\,\overline{m}}{\pi\ D_{out}^2}\right)^2 \left[\left(\frac{x\,\rho_f + (1-x)\,\rho_g}{\rho_f\ \rho_g}\right)_1 - \left(\frac{x\,\rho_f + (1-x)\,\rho_g}{\rho_f\ \rho_g}\right)_3\right] \qquad (19)$$

$$\overline{V_{out}} = \frac{\pi}{4}\ D_{out}^2\ L_{out} \qquad (20)$$

$$\frac{1}{\sqrt{f(D_{out})}} = -2\ \log\left(\frac{\varepsilon\ /\ D_{out}}{3.7} + \frac{2.51}{Re\ \sqrt{f(D_{out})}}\right) \qquad (21)$$

where the average properties of quality($\overline{x}$), pressure($\overline{P}$) and density($\overline{\rho}_{out}$) are estimated from the values at the positions of outlet header and fuel channel exit, such as: $\overline{x} = (x_1 + x_3)/2$; $\overline{P} = (P_1 + P_3)/2$; $\overline{\rho}_{out} = (\rho_1 + \rho_3)/2$. Therefore, the equivalent outlet feeder diameter and length are obtained based on the average properties for the outlet feeder in each channel group.

5. Results and Discussion

Based on the methodology discussed above, the equivalent feeder diameters and lengths obtained for each channel group are shown in Table 3. In this table, the average pressure drop and the standard deviation for each group are also summarized. Note that, in general, the higher power inner channels tend to have larger equivalent diameter, and smaller pressure drops in both inlet and outlet feeders. The equivalent feeder lengths vary as they are largely dependent on the location in the core.

The average fuel channel exit quality for all channel groups is 3.04%, which is very close to the design value of 3%. The average ratio of channel/mass flow rate for all channel groups is in the range of 240±1.1%. The small deviation (±1.1%) indicates that mass flow rate is proportional to channel power.

6. Conclusion

This paper mainly concentrated on the development of a methodology for calculating equivalent inlet and outlet feeder diameter and length of a selected group of channels in a CANDU reactor core. The methodology includes an estimation of representative parameters (pressure, density, quality) at the fuel channel inlet and exit, based on given conditions in the inlet/outlet headers.

Table 3. Equivalent Feeder Geometry and Characteristics of Representative Parameters

Name of Group	Inlet Diameter, D_{in} (m) ($\times 10^{-2}$)	Inlet Length, L_{in} (m)	Outlet Diameter, D_{out} (m) ($\times 10^{-2}$)	Outlet Length, L_{out} (m)	Inlet Pressure Drop, $\Delta P_{t,in}$ (kPa) (±%)	Outlet Pressure Drop, $\Delta P_{t,out}$ (kPa) (±%)	Channel Exit Quality (%) (±%)	Channel Power/Mass Flow Rate (kW s/kg)
G1	4.15	8.07	5.34	10.12	197.0 (±41.4)	318.8 (±24.5)	2.96 (±8.7)	246.6
G2	4.20	14.66	5.68	16.70	326.4 (±41.1)	367.5 (±19.2)	2.79 (±8.4)	242.8
G3	4.99	8.28	6.40	10.44	176.4 (±20.4)	303.7 (±25.8)	3.01 (±8.7)	239.6
G4	5.05	13.64	7.01	16.38	270.2 (±18.5)	293.6 (±21.0)	3.04 (±6.7)	239.4
G5	5.66	10.52	7.37	13.63	168.0 (±31.9)	269.4 (±7.0)	3.12 (±2.0)	237.2
G6	5.84	13.02	7.64	16.72	175.2 (±20.7)	269.8 (±11.3)	3.18 (±3.2)	239.2
G7	5.55	8.11	7.15	10.84	145.4 (±41.8)	260.9 (±13.3)	3.15 (±3.6)	236.5
G8	6.13	11.30	7.68	15.21	127.3 (±14.5)	255.8 (±8.6)	3.16 (±2.3)	238.7

The methodology was applied to an arbitrary set of 8 channel groups in a symmetrical half-core, and the equivalent feeder geometries for all groups were calculated. The standard deviations of representative parameters for a channel group were also calculated. The estimated equivalent feeder diameter and length will be useful for the transient simulation of the primary heat transport system for a CANDU type reactor.

References

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