# An Experimental Study of Pressure Drop Correlations for Wire-Wrapped Fuel Assemblies

**Moon-Hyun Chun*†, Kyong-Won Seo**
*Department of Nuclear Engineering, Korea Advanced Institute of Science and Technology*
**Seok-Ki Choi, Ho-Yun Nam**
*Korea Atomic Energy Research Institute*

The main objective of the present study is to perform an experimental evaluation of five existing correlations for the subchannel pressure drop analysis of a wire-wrapped fuel assembly. For this purpose, a series of water experiments have been performed using a helical wire-wrapped 19-pin fuel assembly for various test parameters. Four different test sections with different pitch to rod diameter ratios ($P/D$) and wire lead length to rod diameter ratios ($H/D$) have been fabricated. A series of pressure drop measurements were made to obtain friction factors for these four test sections. The new data along with existing data are used to evaluate existing correlations. Both the original and the simplified Cheng and Todreas correlations give the best agreement with experimental data for all flow regions.

**Key Words** : Pressure Drop Correlations, Wire-Wrapped Rod Bundle, Subchannel Analysis

**Nomenclature**

$A$ : Axial average flow area (mm$^2$)
$D$ : Rod diameter (mm)
$D_w$ : Wire spacer diameter (mm)
$D_e$ : Hydraulic equivalent diameter (mm)
$f$ : Friction factor
$H$ : Wire lead length (mm)
$L$ : Axial length (mm)
$P$ : Pressure (Pa)
$P$ : Rod pitch (mm)
$P_w$ : Wetted perimeter (mm)
Re : Reynolds number
$V$ : Flow velocity (m/s)
$X$ : Flow split parameter

**Greek**

$\rho$ : Density (m$^3$/kg)
$\mu$ : Dynamic viscosity (Ns/m$^2$)
$\psi$ : Intermittency factor

**Subscript**

$i$ : Subchannel type index

† First Author
* Corresponding Author,
**E-mail** : chunmh@kaist. ac. kr
**TEL** : +82-42-869-3813 ; **FAX** : +82-42-869-3810
Department of Nuclear Engineering, Korea Advanced Institute of Science and Technology, 373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea. (Manuscript **Recevied** August 31, 2000; **Revised** November 29, 2000)

## 1. Introduction

In order to maintain proper spacing between fuel pins and promote coolant mixing, various types of spacers have been proposed. Helical type wire-spacers have been most widely used in liquid metal reactors (LMR), including the Korea Advanced Liquid Metal Reactor (KALIMER). MATRA-LMR code (Kim and Kim, 1998) has been developed for thermal-hydraulic subchannel analyses of LMR based on the COBRA-IV-I code (wheeler, 1976) and MATRA code (Yoo and Hwang, 1997). MATRA-LMR code is being used to design the KALIMER, and the code requires pressure drop correlations for wire-wrapped LMR rod bundles. Due to the complex wire geometry, a simple equivalent diameter technique is not adequate to accurately predict the pressure drop in a wire-wrapped fuel assembly.

Therefore, a number of attempts have been made by several investigators in the past to develop better correlations for the friction factor applicable in a wire-wrapped fuel assembly.

The main objective of the present study is to experimentally perform a comparative study of five existing correlations and identify the best performing correlations in the subchannel pressure drop analysis of a wire-wrapped fuel assembly. To the knowledge of present authors, there is no existing comparative study which shows the relative performance of various existing correlations. The results of this study, therefore, would be useful to analysts using a subchannel analysis code for LMR design. A series of water experiments have been performed using a helical wire-wrapped 19-pin fuel assembly for various combinations of test parameters. Four different test sections with different pitch to rod diameter ratios ($P/D$) and wire lead length to rod diameter ratios ($H/D$) have been fabricated. A series of pressure drop measurements were made to obtain friction factors for these four test sections. A total of 293 data samples were obtained.

## 2. Pressure Drop Correlations

The pressure drop of incompressible flow is calculated from the following equation:

$$\Delta P=f\frac{L}{D_e}\frac{\rho V^2}{2} \tag{1}$$

where $L$ is the distance across which the pressure drops were measured. There are three types of subchannels (i. e., interior, edge, and corner) assuming that the axial pressure drop across each subchannel of a fuel assembly is the same due to the same upstream and downstream boundary conditions. Figure 1 shows the definition of the three types of flow subchannels. The pressure drop across subchannel $i$ is

$$\Delta P_i=f_i\frac{L}{D_{ei}}\frac{\rho V_i^2}{2} \tag{2}$$

Where $f_i$ is the effective friction factor in the subchannel $i$ (i. e., 1, 2 and 3 are interior, edge and corner, respectively).

The bundle and subchannel friction factors are given by Eqs. (1) and (2). The existing friction factor correlations selected for evaluation in the present work are summarized in Table 1.

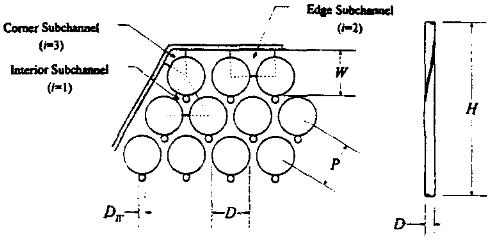



**Fig. 1** Definitions of flow subchannels for a wire spacer of typical 19-pin fuel assembly

### 2.1 Novendstern model

Novendstern (1972) developed a semi-empirical model that can predict the pressure loss for turbulent flow in a hexagonal array of rods with a wire-spacer. The model is based on the concept that the pressure drop in a subchannel can be obtained by first calculating the pressure drop of a smooth pipe using an equivalent diameter concept and then multiplying the result by an empirical correlation factor $M$ that includes the effect of wire spacers.

The bundle friction factor is given by:

$$f=f_iX_i^2\frac{D_e}{D_{ei}} \tag{3}$$

where $f_i$ is the friction factor of subchannel $i$ and $X_i$ is the flow split parameter of subchannel $i$. The subchannel friction factor $f_i$ is defined as follows:

$$f_i=f_sM \tag{4}$$

where

$$M=\left\{\frac{1.034}{(P/D)^{0.124}}+\frac{29.7(P/D)^{6.94}\mathrm{Re}_i^{0.086}}{(H/D)^{2.239}}\right\}^{0.885} \tag{5}$$

In the present work, the Blasius relation has been used as a smooth pipe friction factor in Eq. (4).

The flow split parameter is calculated from the total mass flow assuming an equal pressure drop for each subchannel:

**Table 1** Typical existing friction factor correlations selected

| Author | a) Rods<br>b) Re<br>c) $P/D$<br>d) $H/D$ | Correlations for the Friction Factor<br>a) for Laminar Region<br>b) for Transition Region<br>c) for Turbulent Region |
|---|---|---|
| Novendstern (1972) | a) 197~217<br>b) 2,600~200,000<br>c) 1.06~1.42<br>d) 8.0~96.0 | c) $f=f_i X_i^2 \frac{D_e}{D_{ei}}$<br>where $f_i$ for Eq. (4) and $X_i$ for Eq. (6) |
| Rehme (1973) | a) 7~37<br>b) 1,000~300,000<br>c) 1.125~1.417<br>d) n/a | $f=\left[\frac{64}{\mathrm{Re}}F^{0.5}+\frac{0.0816}{\mathrm{Re}^{0.133}}F^{0.9335}\right]\frac{P_{wb}}{P_{wt}}$ for all flow regions<br>where $F$ is defined in Eq. (7). |
| Engel et al. (1979) | a) 61<br>b) 50~40,000<br>c) 1.079~1.082<br>d) 7.7~7.782 | a) $f=\frac{320}{\mathrm{Re}\sqrt{H}}\left[\frac{P}{D}\right]^{1.5}$<br>b) $f=\frac{100}{\mathrm{Re}}\sqrt{1-\psi}+\frac{0.55}{\mathrm{Re}^{0.25}}\sqrt{\psi}$<br>c) $f=\frac{0.55}{\mathrm{Re}^{0.25}}$<br>where $\psi=\frac{\mathrm{Re}-400}{4600}$ |
| Cheng and Todreas (1986) | a) 7~217<br>b) 400~100,000<br>c) 1.067~1.35<br>d) 4~52 | a) $f=\frac{C_{fL}}{\mathrm{Re}}$<br>b) $f=\left[\frac{C_{fT}}{\mathrm{Re}^{0.18}}\right]\psi^{1/3}+\left[\frac{C_{fL}}{\mathrm{Re}}\right](1-\psi)^{1/3}$<br>c) $f=\frac{C_{fT}}{\mathrm{Re}^{0.18}}$<br>where $\psi$, $C_{fL}$ and $C_{fT}$ are defined in Eqs. (14)~(16). |

$$X_i=\frac{V_i}{V}=\frac{\sum_{i=1}^{3} N_i A_i}{\sum_{j=1}^{3} N_j A_j\left(\frac{D_{ej}}{D_{ei}}\right)^{0.714}} \tag{6}$$

$N_i$ and $A_i$ are the number and the area of subchannel $i$, $A$ is the total flow area, $V$ is the bundle average flow velocity, and $D_e$ is the bundle equivalent diameter.

### 2.2 Rehme model

Rehme (1972) introduced an effective velocity to take into account of the swirl flow velocity around the rods caused by the wire-wraps. The square of the ratio of this effective velocity to the bundle average axial velocity was correlated to be

$$F=\left[\frac{V_{eff}}{V}\right]^2 = \left[\frac{P}{D}\right]^{0.5}+\left[7.6\frac{(D+D_w)}{H}\left[\frac{P}{D}\right]^2\right]^{2.16} \tag{7}$$

A modified friction factor is defined as follows:

$$f'=\frac{f}{F}\frac{P_{wt}}{P_{wb}}=\left[\frac{64}{\mathrm{Re}'}+\frac{0.0816}{\mathrm{Re}'^{0.133}}\right] \tag{8}$$

where $P_{wb}$ is the wetted perimeter of the rod bundle and $P_{wt}$ is the total wetted perimeter. A modified Reynolds number is obtained by

$$\mathrm{Re}'=\mathrm{Re}\sqrt{F} \tag{9}$$

The friction factor in Eq. (1) can be expressed using Eqs. (7)-(9) as,

$$f=\left[\frac{64}{\mathrm{Re}}F^{0.5}+\frac{0.0816}{\mathrm{Re}^{0.133}}F^{0.9335}\right]\frac{P_{wb}}{P_{wt}} \tag{10}$$

### 2.3 Engel et al. model

Engel et al. (1979) introduced the intermittency factor $\psi$ to correlate the friction factor in the transition region based on their experimental results. For the transition region from turbulent to laminar flow that occurred over the Reynolds number range from 5,000 to 400:

$$\psi=\frac{Re-400}{4600} \quad (11)$$

They proposed a simple friction factor correlation that can be applied to laminar, transition and turbulent regions. Since their correlation is based on their limited data, its applicability appears to be limited to their data.

### 2.4 Cheng and Todreas model

Cheng and Todreas (1986) developed their friction factor correlations using an extensive amount of experimental data. In this model, the bundle friction factor and the subchannel friction factors for each subchannel are derived, and the correlations are applicable for all flow regimes. Only a brief outline of the model is shown here for reference. Also they have proposed a simplified form of the original model. Their empirical correlations for the laminar and turbulent flows are as follows:

$$\log(Re_L/300)=1.7(P/D-1.0) \quad (12)$$

$$\log(Re_T/10{,}000)=0.7(P/D-1.0) \quad (13)$$

For the transition region, they used an intermittency factor:

$$\psi=\log(Re/Re_L)/\log(Re_T/Re_L) \quad (14)$$

Coefficients of $C_{fL}$ and $C_{fT}$ are given by

$$C_{fL}=\left\{-974.6+1612.0\left(\frac{P}{D}\right)-598.5\left(\frac{P}{D}\right)^2\right\}\left(\frac{H}{D}\right)^{0.06-0.085(P/D)} \quad (15)$$

$$C_{ft}=\left[0.8063-0.9022\log\left(\frac{H}{D}\right)+0.3526\left\{\log\left(\frac{H}{D}\right)\right\}^2\right]\times\left(\frac{P}{D}\right)^{9.7}\left(\frac{H}{D}\right)^{1.78-2(P/D)} \quad (16)$$

Both original and simplified correlations are included in the present evaluation.

## 3. Experiments

### 3.1 Experimental apparatus

A schematic diagram of the test loop for a 19-pin wire wrapped fuel assembly is shown in Fig. 1.

**Table 2** Specifications of test sections

| Test Section | | A2 | A3 | B2 | B3 |
|---|---|---|---|---|---|
| Lead to Diameter Ratio | $H/D$ | 25.0 | 37.5 | 25.0 | 37.5 |
| Pitch to Diameter Ratio | $P/D$ | 1.178 | 1.178 | 1.256 | 1.256 |
| Equiv. Diameter | $De$ | 3.68 | 3.68 | 4.75 | 4.75 |
| Outer Diameter (mm) | $D$ | 8.0 | 8.0 | 8.0 | 8.0 |
| Pitch (mm) | $P$ | 9.44 | 9.44 | 10.04 | 10.04 |
| Length (mm) | $L$ | 1300.0 | 1300.0 | 1300.0 | 1300.0 |
| Wire Diameter (mm) | $D_w$ | 1.4 | 1.40 | 2.0 | 2.0 |
| Lead Length (mm) | $H$ | 200.0 | 300.0 | 200.0 | 300.0 |

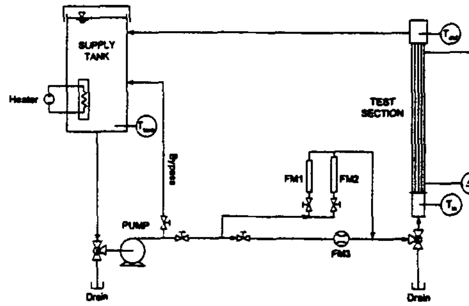



**Fig. 2** Schematic diagram of the test loop

The specifications of four test sections of the 19-pin assembly are listed in Table 2. Three flowmeters (FM1, FM2 and FM3) are installed to measure the volumetric flow rate in the test loop as shown in Fig. 2. Two rotameters are installed in parallel. One has a 8.3 *lpm* (FM1) range and the other has a 37.8 *lpm* (FM2) range. One magnetic flowmeter (FM3) of 400.0 *lpm* capacity is installed in parallel with the rotameters to measure the high flow rate. Three different differential pressure transducers (1.5 *kPa*, 7.5 *kPa* and 185.0 *kPa*) are used to measure the pressure drop. One of three transducers was selected depending on the pressure range.

### 3.2 Pressure drop measurement

Pressure drops are measured at the duct wall pressure taps. Upstream and downstream pressure taps were installed on four faces of hexagonal duct wall. At each axial location, four pressure tap values are connected to one tube to obtain an average value and minimize the disturbance from the wire-spacer orientation. The taps are installed 50 mm away from both ends of the rod to minimize the inlet and outlet disturbances. The distance between the upstream and the downstream pressure taps is 1,100 mm.

## 4. Results and Discussion

A series of experiments have been performed changing the flow rate and test sections with different geometric parameters (i.e., $P/D$ and $H/D$). The present experiment has focused on examining the effects of these parameters on the bundle friction factor and evaluating existing correlations against previous and new data. The available experimental friction factor data sets are summarized in Table 3.

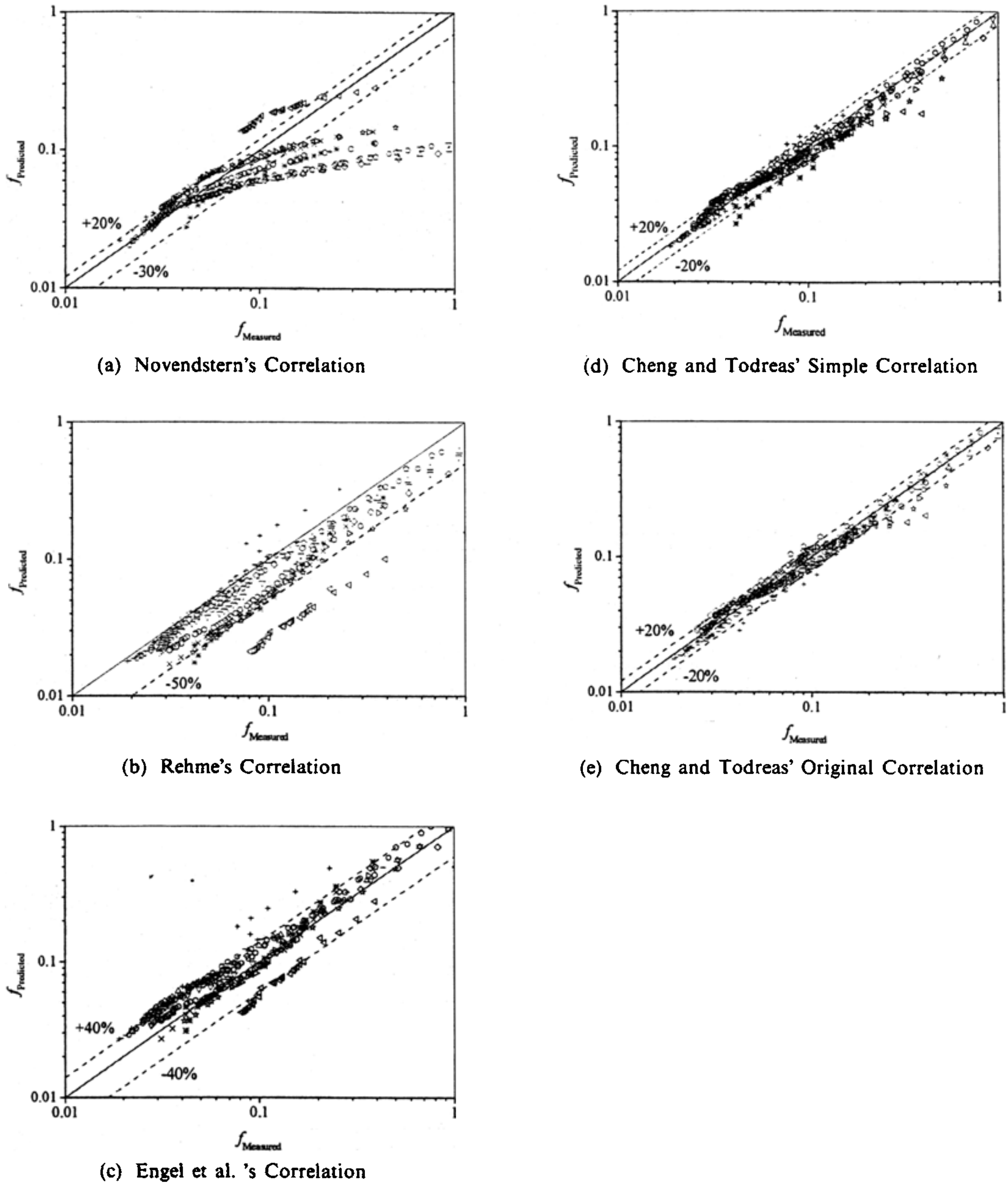
Comparisons of all the available measured data with existing empirical correlations are shown in Figs. 3. Figure 3(a) shows the comparison of Novendstern's correlation (1972) with the measured data. Novendstern's correlation agrees well with experimental data when the magnitude of the friction factor is small (i. e., $f_b \leq 0.04$, $Re \leq Re_L$ in Eq. (12)). The deviation between the correlation and the data becomes larger as the magnitude of the friction factor increases (i. e., $f_b > 0.04$, $Re > Re_L$). The predictions of Novendstern's correlation agree fairly well with the data only in the turbulent region. Comparisons of Rehme's correlation (1972) with the measured data are shown in Fig. 3(b). Some data agree quite closely with Rehme's predictions while some data with different $P/D$ and $H/D$ deviate from Rehme's correlation. Thus, Rehme's correlation does not predict the effects of $P/D$ and $H/D$. Figure 3(c) shows that the Engel et al.'s correlation (1979) predicts the friction factor poorly in all flow regions and its agreement with data is inconsistent. One should note that Engel et al.'s correlation depends only on the Reynolds number, and the effects of $P/D$ and $H/D$ are not considered.

**Table 3** Summary of the available experimental data

| | | Number of rods | P/D | H/D | Number of data |
|---|---|---|---|---|---|
| Present Study | A2 | 19 | 1.178 | 25.0 | 26 |
| | A3 | 19 | 1.178 | 37.5 | 28 |
| | B2 | 19 | 1.256 | 25.0 | 207 |
| | B3 | 19 | 1.256 | 37.5 | 32 |
| Chiu (1978) | | 61 | 1.067 | 4.0 | 43 |
| | | 61 | 1.067 | 8.0 | 35 |
| Engel (1979) | | 61 | 1.982 | 7.78 | 15 |
| Cheng (1982) | | 37 | 1.154 | 13.4 | 45 |
| Itoh (1981) | | 127 | 1.176 | 38.0 | 23 |
| | | 169 | 1.214 | 47.4 | 18 |
| Marten (1982) | | 37 | 1.041 | 17.01 | 19 |
| | | 37 | 1.072 | 8.34 | 20 |
| | | 37 | 1.101 | 12.31 | 19 |
| Spencer (1980) | | 217 | 1.252 | 51.7 | 21 |
| Total | | 19 ~217 | 1.067 ~1.982 | 4.0 ~47.4 | 551 |

The existence of wire strongly affects the flow field and, therefore, the correlations which do not take into account of the effects of $P/D$ and $H/D$ give poor results. The simplified correlation of Cheng and Todreas (1986) is compared with the measured data in Fig. 3(d). Most of the data agree very closely with the prediction to within $\pm 20\%$. In Fig. 3(e), the original correlation of Cheng and Todreas is compared with the measured data. Some of the data agree more closely with this correlation than the simplified correlation, particularly in the transition and the turbulent regions where the magnitude of the friction factor is relatively small.

Figure 4 shows the friction factor versus Reynolds number curves obtained from five existing correlations along with the present experimental data obtained with Test Section B2. The flow transition between the laminar and turbulent regions is quite smooth and continuous. Compared to a circular tube, departure from the laminar flow occurs at a lower Reynolds number, while the fully turbulent flow occurs at a higher




(a) Novendstern's Correlation

(d) Cheng and Todreas' Simple Correlation

(b) Rehme's Correlation

(e) Cheng and Todreas' Original Correlation

(c) Engel et al. 's Correlation

**Fig. 3** Comparisions of the existing friction factor correlations with the measured friction factor data

Reynolds number. Rehme's model underpredicts the friction factor, while Engel et al.'s correlation greatly overpredicts the friction factor for overall flow regions as already observed in Figs. 3(b) and 3(c). Both correlations of Cheng and Todreas agree well with the friction factor data for all flow regions. The Novendstern correlation agrees well with the data in the turbulent flow region, but this correlation slightly overpredicts in the transition region.

The uncertainty of the present friction factor in Eq. (1) has been found to be around 9~14% for Re<4,500 and 2~6% for Re≥4,500, respectively, with 95% confidence interval.

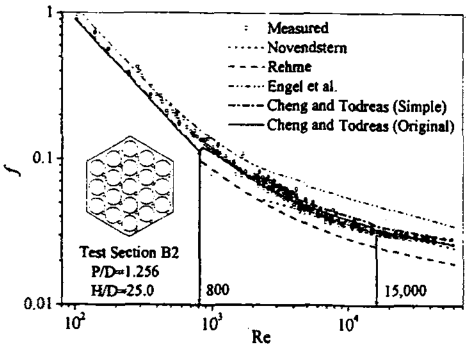



**Fig. 4** Reynolds number vs. friction factor (Test Section B2)

## 5. Conclusions

A compartive study of representative correlations of friction factors has been performed to identify the best performing correlations for the subchannel pressure drop analysis of a wire-wrapped fuel assembly. From the results, the following conclusions can be made.

(1) Novendstern's correlation agrees fairly well with experimental data in the turbulent region. This model, therefore, should be used only in the turbulent flow region.

(2) Reheme's correlation does not represent the effects of $P/D$ and $H/D$ sufficiently well, and this correlation consistently underpredicts the friction factor for all flow regions.

(3) Engel et al.'s correlation depends only on the Reynolds number and the effects of $P/D$ and $H/D$ are not properly represented. This correlation greatly overpredicts the friction factor for all flow regions.

(4) Both the original and the simplified Cheng and Todreas' correlations show good agreement with experimental data for all flow regions. The difference between the original and the simplified correlations is less than 1%.

(5) Therefore, it is recommended that both correlations of Cheng and Todreas be used all flow regions.

## Acknowledgement

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