*PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 46, NO. 1, PP. 15–27 (2002)*

# THEORETICAL STUDY IN SINGLE-PHASE FORCED-CONVECTION HEAT TRANSFER CHARACTERISTICS FOR NARROW ANNULI FUEL COOLANT CHANNELS

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Received: March 7, 2000

## Abstract

The heat transfer characteristics of downflow in the single-phase forced-convection will be investigated theoretically with narrow vertical annuli sub-channels (WWR-M2 channel) using THMOD2 code. The main objective for this study is to investigate in turbulent flow region the applicability of existing heat transfer equations (i.e. Dittus-Boelter, Colburn, and so on) in the narrow vertical annuli channel, which is modelling and simulating sub-channel of 3 mm spacing (gap) and 600 mm in active length in the fuel elements for thermal hydraulic analysis tasks of the WWR-M2 research reactor or any other type. As a result, it was revealed that by use of equivalent hydraulic diameter, existing correlations are applicable to a WWR-M2 channel as narrow as 3 mm in gap for turbulent flow though the precision and Reynolds number are different among the heat transfer correlations. The New heat transfer equation for sub-channels of WWR-M2 channel heated from one side or both sides will be proposed.

*Keywords:* Research reactor, thermal hydraulics, reactor heat transfer, heat transfer correlation, and reactor safety, WWR-M2 channel.

## 1. Introduction

The problem that is addressed to in this study is the applicability of the existing heat transfer correlations for single-phase downflow forced-convection heat transfer characteristics for a vertical annuli channel simulating sub-channels of the fuel elements of the WWR-M2 research reactor thermal hydraulic analysis. Each WWR-M2 fuel assembly has three coaxial annuli fuel elements with 3, 3, 3.18, and 1.58 mm gaps with 600 mm in active length.

In this type of WWR-M2 research reactor, and for the condition of normal operation at 10 $MW_{th}$, fuel elements are cooled by downward flow at the average coolant velocity of 3 m/sec without allowing nucleate boiling condition anywhere in the reactor core.

The objectives of this theoretical study are, therefore, to investigate the following tasks for forced-convection heat transfer in a vertical coaxial annuli channel simulating sub-channels of a WWR-M2 fuel coolant assembly.

1. The applicability of the existing heat transfer correlations derived from circular tubes to an annuli whose gap is as narrow as 3 mm for high coolant velocities for downflow condition.
2. Evaluations of heat transfer coefficients for downflow in the coaxial annuli channel.

To investigate the above tasks for the coaxial annuli channel as shown in *Fig. 1.a* and *1.b* two sub-channels heated from one side (A and D) and another heated from both sides (B and C) were used in the coaxial channels.

The differences in heat transfer characteristics between sub-channels of WWR-M2 channel heated from both sides and from one side are also investigated to help in the understanding of the effects of differences of heating conditions.

The study investigation and results data are accomplished by using THMOD2 code [6], [7]. This code was developed for the thermal hydraulics analysis of a water-cooled nuclear research reactor fuel coolant channel.

## 2. WWR-M2 Reactor Core Description

The WWR-M2 [1]–[5] is a cylindrical tank type reactor. The reactor core is placed 5.145 m below the surface of the reactor tank, which is open to atmospheric pressure. The diameter of the tank is 2300 mm, and its height is 5685 mm. The heavy concrete reactor-shielding block is situated in a rectangular semi-hermetically sealed reactor hall.

The base of the reactor core is a hexagonal grid plate, with 397 identically formed holes. The fuel assemblies and the beryllium displacers can be put into these holes, as well as the guide tubes of the 18-absorber rods. The equilibrium core size (in this study) consists of 223 fuel assemblies, and the control rods, beryllium displacers and isotopes production channels, occupy the remaining core positions. A fixed beryllium reflector of 20-cm average thickness surrounds the core. The fuel assembly type is WWR-SM as shown in *Fig. 1.a*, *1.b* (consists of 3 coaxial fuel elements). The innermost is a tube, this is followed by a second fuel element with an annulus cross-section, and the third fuel element (outer) is a hexagonal shape.

## 3. THMOD2 Computer Code

The THMOD2 (**T**hermal **H**ydraulics **M**odelling version **2**) [6], [7] code is a one-dimensional computer program (axial direction) and it provides a capability for analysis of the steady state thermal – hydraulics of research reactors in which coaxial annuli and plates type fuel elements are adopted. In this code, there are subroutines to calculate temperature distribution in fuel elements. The THMOD2 code can calculate fuel temperatures under forced convection cooling mode with downflow direction. A heat transfer package is used for calculating heat transfer coefficient, DNB heat flux etc.

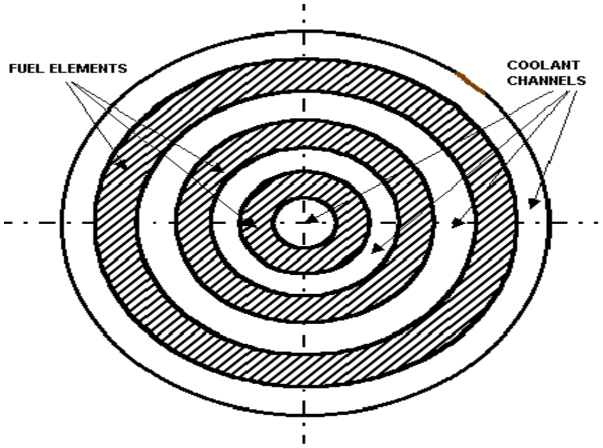
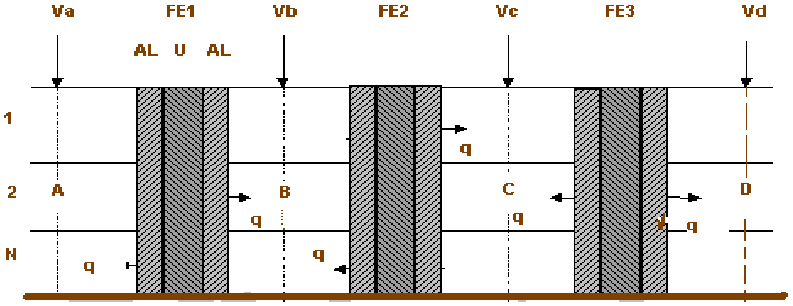


*Fig. 1.a.* Coaxial WWR-M2 Fuel Coolant Channel



| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $r$ | 0 | | | | | | | | | | | | 18.38 |
| $r_{AL}$ | | 3.0 | | 5.5 | | 8.5 | | 11.0 | | 14.18 | | 16.80 | |
| $\Delta r_U$ | | | 0.7 | | | | 0.7 | | | | 0.74 | | |
| $\Delta r_{H2O}$ | 3.0 | | | | 3.0 | | | | 3.18 | | | | 1.58 |
| $d_e$ | 6.0 | | | | 6.0 | | | | 6.175 | | | | 6.62 |
| $C$ | | 18.85 | | 34.56 | | 53.41 | | 69.12 | | 93.53 | | 110.85 | |
| | 18.85 | | | | 87.97 | | | | 162.65 | | | | 110.85 |
| $A_{AL+U}$ | | | 66.76 | | | | 153.15 | | | | 255.50 | | |
| $A_{H2O}$ | 28.27 | | | | 131.90 | | | | 251.20 | | | | 174.1 |

* All dimensions are in mm and mm$^2$

*Fig. 1.b.* Axial Cross Section of WWR-M2 Fuel Coolant Channel

The heat transfer package was especially developed for research reactors, which operated under low pressure and low temperature conditions using coaxial

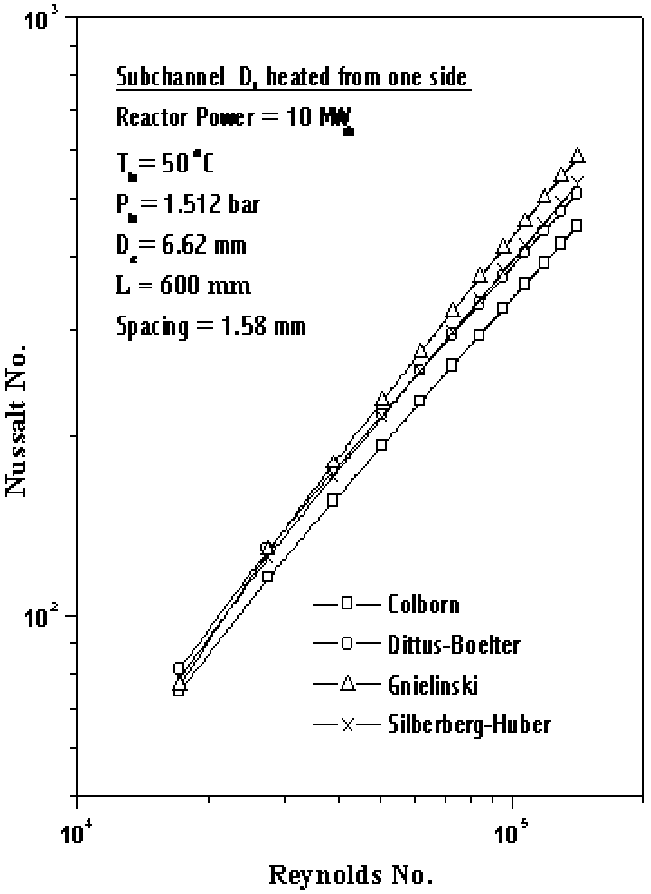


*Fig. 2.* The comparison of theoretical results of heat transfer correlations for WWR-M2 sub-channel D heated from one side

annuli and plate-type fuel elements, just like the WWR-M2 reactor.

## 4. Heat Transfer Characteristics

The local bulk temperature $T_b$ of coolant, average coolant velocity $V$ in the flow sub-channels of WWR-SM fuel coolant channel, fuel element surface heat flux $q''$ (W/cm$^2$), and local fuel element surface temperature $T_w$ are the fundamental variables required to identify heat transfer characteristics in the single-phase forced-convection heat transfer.

Heat flux is calculated by THMOD2 code as $q''(z) = q''_{o_i} \cos(\pi z/H)$, where

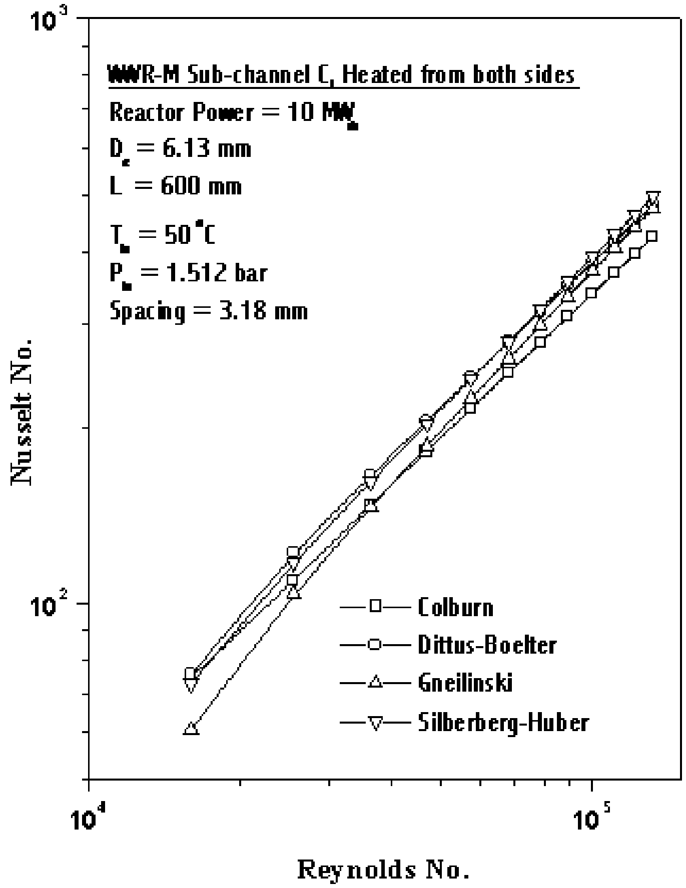


*Fig. 3.* The comparison of theoretical results of heat transfer correlations for WWR-M2 sub-channel C heated from both sides

$q''_{o_i}$ is the maximum cladding surface heat flux and $i$ is the surface number ($i = 1 \ldots 6$), in the case of sub-channels B and C are heated from both sides, but in the case of sub-channels A and D are heated from one side only. The maximum surface heat fluxes are shown in *Table* 1

The axial temperature distribution of coolant along the sub-channels is calculated by [8], [9]:

$$T_b(z) = T_{in} + \frac{q''_{i_{\max}} C_i H_e}{\pi c_p \dot{m}_i} \left[ \sin\left(\frac{\pi AL}{H_e}\right) + \sin\left(\frac{\pi z}{H_e}\right) \right] \tag{1}$$

and the axial temperature distribution of the cladding surface along the sub-channels

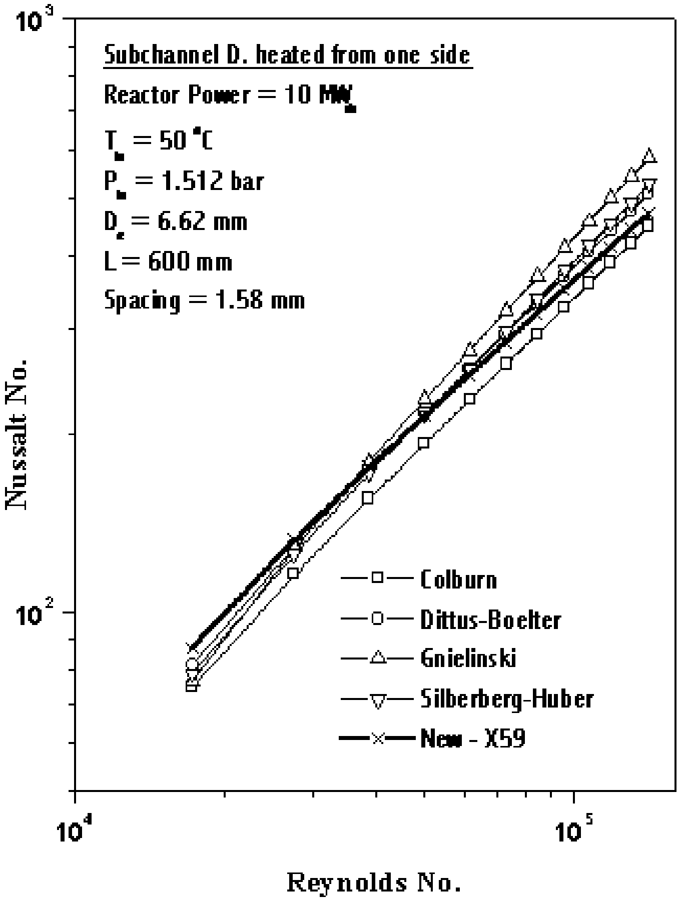


*Fig. 4.* The comparison of theoretical results of new X59 and existing heat transfer correlations for WWR-M2 sub-channel D heated from one side

*Table 1.* Maximum cladding surfaces heat fluxes at normal reactor operation (10 $\text{MW}_{th}$, and 1750 $\text{m}^3$/hr)

| Surface | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Heat flux, [W/$\text{cm}^2$] | 65.13 | 53.52 | 60.74 | 55.05 | 79.27 | 80.93 |

surfaces is calculated by:

$$T_w(z) = T_{in} + \frac{q''_{i_{\max}} C_i H_e}{\pi c_p \dot{m}_i} \left[ \sin\left(\frac{\pi AL}{H_e}\right) + \sin\left(\frac{\pi z}{H_e}\right) \right] + \frac{q''_{i_{\max}}}{\alpha} \cos\left(\frac{\pi z}{H_e}\right). \quad (2)$$

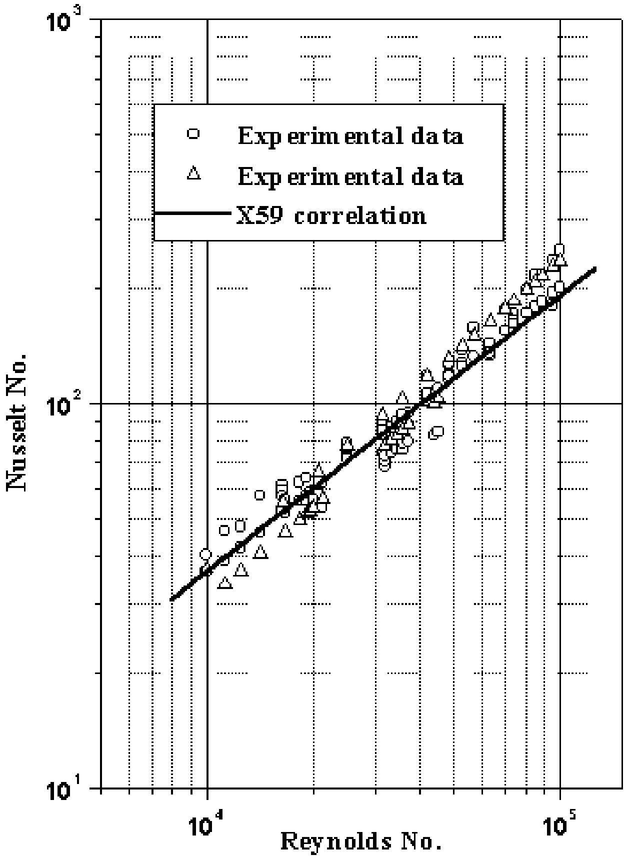


*Fig. 5.* Comparison of X59 correlation with data of several authors for heat transfer of liquids in concentric circular annuli and vertical rectangular channel as (WWR-SM sub-channel D heated from one side)

The existing heat transfer correlations for circular tubes proposed by DITTUS-BOELTER [8], SILBERBERG-HUBER [9], COLBURN [10] and GNIELINSKI [11], are shown below:

Dittus-Boelter:
$$\mathrm{Nu} = 0.023\,\mathrm{Re}_b^{0.8}\mathrm{Pr}_b^{0.4} \tag{3}$$

Silberberg-Huber:
$$\mathrm{Nu} = 0.015\,\mathrm{Re}_b^{0.85}\mathrm{Pr}_b^{0.3} \tag{4}$$

Colburn:
$$\mathrm{Nu} = 0.023\,\mathrm{Re}_f^{0.8}\mathrm{Pr}_f^{0.3} \tag{5}$$

Gnielinski:
$$\mathrm{Nu} = \frac{(f/8)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7(\mathrm{Pr}^{2/3})\sqrt{f/8}}[1 + d/L)^{2/3}] \tag{6}$$

where $f$ is the friction factor calculated by using the Filonenko correlation [11] as follows:

$$f = (1.82 \log_{10} \mathrm{Re} - 1.64)^{-2}, \tag{7}$$

where Nu is the Nusselt number, Pr is the Prandtl number and $\mu$ is the dynamic viscosity. Subscripts $b$, $f$ and $s$ indicate that coolant physical properties are evaluated at bulk temperature $T_b$ of coolant, film temperature $T_f = \dfrac{(T_b + T_w)}{2}$ of coolant and surface temperature $T_w$ of heating fuel elements on flow sub-channels side, respectively.

The Nu and Re are defined as $\mathrm{Nu} = \dfrac{\alpha D_e}{k}$ and $\mathrm{Re} = \dfrac{D_e V \rho}{\mu}$, where $\alpha$ is the heat transfer coefficient, $D_e$ is the equivalent hydraulic diameter of flow sub-channel, $k$ is the thermal conductivity of the coolant, $V$ is the coolant velocity in the sub-channel in the flow WWR-SM channel.

## 5. Calculations Procedure

The international correlations of heat transfer correlations as described above as algorithms functions in the construction of the THMOD2 code, were applied for WWR-M2 fuel coolant sub-channel. These results of the correlations were compared in the operating pressure range of WWR-M2 reactor and the coolant inlet temperature is 50 °C with changing the inlet of reactor core volume flow rate of coolant from 500 to 4500 $\mathrm{m}^3$/hr. *Fig.* 2 and *Fig.* 3 show the comparison of theoretical results of the existing heat transfer correlations as a function of coolant volume flow rate of the WWR-M2 reactor core fuel coolant channel, downflow condition and in the turbulent region for sub-channels D and C heated from one side and both sides, respectively. The heat transfer correlations data were generated by THMOD2 code for WWR-M2 fuel coolant channel at different conditions (i.e., as a function of: $P$, $\dot{V}$, $D_e, \ldots$) with using the existing international heat transfer correlations well fitted and correlated empirically as follows:

$$\mathrm{Nu} = 0.045\,\mathrm{Re}_b^{0.74}\,\mathrm{Pr}_b^{0.35}. \tag{8}$$

The new heat transfer correlation (X59) and ranges of parameters of the data used in developing the correlation are:

Channel spacing [mm] ≤ 3
Reynolds number range = 13816 – 141213
Pressure [bar] = near atmospheric
Heated length [mm] ≤ 600
Inlet sub-cooled [°C] = 50
Geometries = annuli tubes and rectangular channel

*Fig. 3* shows the comparison results for WWR-M2 channel that were generated by THMOD2 between the X59 correlation and the existing heat transfer correlations in the same operating conditions in the sub-channel D as an example.

The maximum cladding surface temperatures were calculated by THMOD2 code using the existing and the X59 heat transfer correlations and are shown in

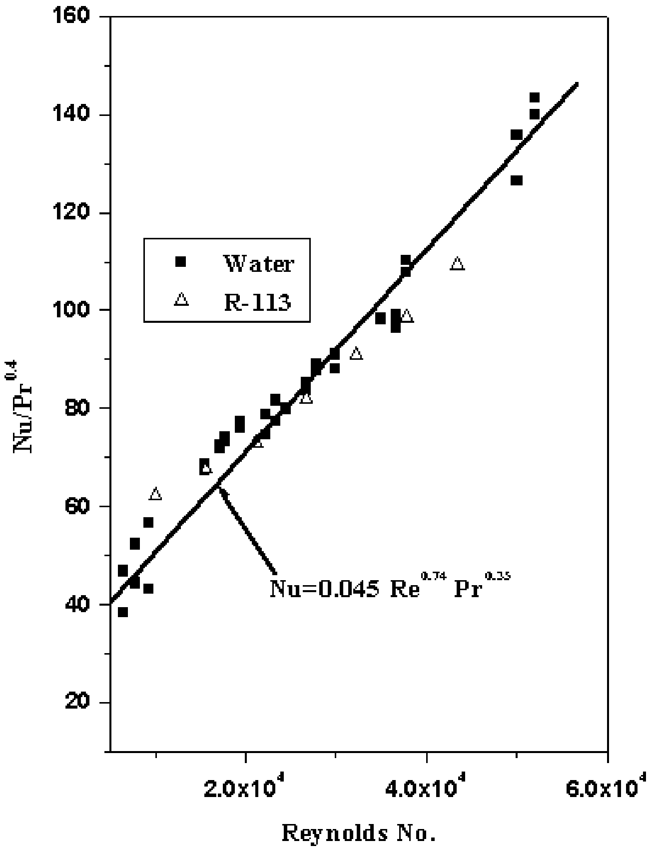


*Fig. 6*. Comparison of X59 correlation with data of several authors for heat transfer of liquids in concentric circular annuli and vertical rectangular channel (R-113 from THORSEN et al [13], and water from SANI [13]) downflow condition

*Table* 2. *Table* 3 shows the calculated results using the existing and the X59 correlations for the fuel maximum centerline temperatures.

The average coolant velocities and heat transfer coefficients calculated by THMOD2 code for WWR-M2 sub-channels using the existing and X59 heat transfer correlations are shown in *Table* 4.

*Table 2.* Maximum cladding surfaces temperature [°C] at normal reactor operation (10 $MW_{th}$, and 1750 $m^3$/hr)

| Correlation | Surface 1 [°C] | 2 [°C] | 3 [°C] | 4 [°C] | 5 [°C] | 6 [°C] |
|---|---|---|---|---|---|---|
| X59 | 100.18 | 94.36 | 98.84 | 92.97 | 109.19 | 110.17 |
| Colburn | 105.21 | 100.82 | 106.19 | 98.87 | 117.40 | 118.43 |
| Dittus-Boelter | 100.29 | 94.23 | 98.70 | 92.68 | 108.80 | 109.59 |
| Gnielinski | 99.97 | 93.96 | 98.39 | 92.57 | 108.65 | 109.57 |
| Silberberg-Huber | 101.31 | 94.80 | 99.35 | 93.29 | 109.82 | 110.39 |

*Table 3.* Maximum fuel centerline temperature at normal reactor operation (10 $MW_{th}$, and 1750 $m^3$/hr) in the WWR-M2 channel

| Correlation | Fuel Element 1 [°C] | Fuel Element 2 [°C] | Fuel Element 3 [°C] |
|---|---|---|---|
| X59 | 138.70 | 133.91 | 156.87 |
| Colburn | 148.77 | 143.03 | 173.42 |
| Dittus-Boelter | 138.91 | 134.10 | 155.77 |
| Gnielinski | 138.27 | 133.48 | 155.77 |
| Silberberg-Huber | 140.96 | 135.83 | 157.38 |

## 6. Study Results

*Fig.* 5 and *Fig* 6 show the comparison of experimental results [12], [13] for downflow with X59 correlation. In both cases there are vertical channels and concentric annuli for water and R-133. This comparison shows the good agreement between the results of X59 correlation and the experimental data.

*Table* 4 shows the statistical comparison between results of X59 and Dittus-Boelter correlations with the experimental data.

*Table 4*. The average values for heat transfer coefficient, coolant velocities, Nusselt number, and Reynolds number calculated by using the several heat transfer correlations at normal operation of the WWR- M2 reactor

| Correlation | Sub-channel | $\alpha$ [W/cm$^2$·K] | $V$ [m/sec] | Nu [–] | Re [–] |
|---|---|---|---|---|---|
| Dittus-Boelter | A | 1.84 | 2.71 | 169.75 | 36943.00 |
| | B | 1.87 | 2.70 | 172.50 | 38294.96 |
| | C | 1.89 | 2.90 | 185.14 | 41470.18 |
| | D | 1.93 | 2.94 | 198.86 | 44566.31 |
| X59 | A | 1.83 | 2.69 | 169.41 | 36732.51 |
| | B | 1.87 | 2.68 | 172.12 | 38084.21 |
| | C | 1.88 | 2.88 | 183.71 | 41237.46 |
| | D | 1.90 | 2.92 | 193.56 | 44317.21 |
| Colburn | A | 1.54 | 3.03 | 143.38 | 33627.59 |
| | B | 1.54 | 3.03 | 143.38 | 33627.59 |
| | C | 1.57 | 3.16 | 155.30 | 37160.13 |
| | D | 1.59 | 3.26 | 163.98 | 39773.26 |
| Gnielinski | A | 1.52 | 2.69 | 140.67 | 36732.51 |
| | B | 1.64 | 2.68 | 150.64 | 38084.21 |
| | C | 1.69 | 2.88 | 164.82 | 41237.21 |
| | D | 2.00 | 2.92 | 203.18 | 44317.21 |
| Silberberg | A | 1.79 | 2.71 | 165.55 | 36943.06 |
| | B | 1.84 | 2.70 | 169.08 | 38294.96 |
| | C | 1.86 | 2.90 | 181.88 | 41470.18 |
| | D | 1.90 | 2.94 | 193.16 | 44566.31 |

*Table 5*. The statistical comparison between the experimental data, X59 correlation and Dittus-Boelter correlation for calculation of Nu number

| Method | Mean | Standard deviation | Standard error | Sum | No. |
|---|---|---|---|---|---|
| X59 | 114.37 | 46.03 | 7.1 | 4804 | 42 |
| Dittus-Boelter | 128.52 | 55.43 | 8.6 | 5398 | 42 |
| Experimental | 121.62 | 55.76 | 8.6 | 5108 | 42 |

## 7. Conclusion

This theoretical study investigated the possibility of applicability of the existing heat transfer correlations derived from circular tubes to the vertical annuli channel (WWR-M2) whose small gaps for high coolant velocities for downflow conditions, as a result made clear the following:

1. By using the equivalent hydraulic diameter, the existing heat transfer correlations of COLBURN, DITTUS-BOELTER, GNIELINSKI, and SILBERBERG-HUBER correlations are applicable to a narrow vertical WWR-M2 annuli channel for turbulent flow region.
2. The new heat transfer correlation X59 gives good results compared with the experimental data and existing heat transfer correlations, and we can use this correlation for narrow vertical channel heated from both sides or heated from one side under several operation conditions as described above.

## Acknowledgement

The authors would like to express their hearty gratitude to Prof. Dr. László Rádonyi, head of Department for Energy, Technical University of Budapest, Hungary for his continuous encouragement, valuable suggestions and support for this work. Thanks are also forwarded to Prof. Dr. Tamás Jászay for his suggestions and discussions.

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## Nomenclature

Nu : Nusselt Number
Re : Reynolds Number
Pr : Prandtl Number
$f$ : Friction factor
$d$ : Tube diameter, [m]
$D_e$ : Equivalent hydraulic diameter, [m]
$L$ : Channel length, [m]
$T$ : Temperature, [°C]
$P$ : System pressure, [bar]
$V$ : Coolant velocity, [m/sec]
$\alpha$ : Heat transfer coefficient, [W/cm$^2$·K]
$\rho$ : Coolant density, [kg/cm$^3$]
$\mu$ : Dynamic viscosity, [N·s/m$^2$]
$K$ : Thermal conductivity, [W/cm·k]
$q''_0$ : Maximum heat flux, [W/cm$^2$]
$q''(z)$ : Axial heat flux, [W/cm$^2$]
$\dot{m}$ : Mass flow rate, [kg/sec]
AL : Channel active length, [cm]
$H_e$ : Extrapolated distance, [cm]
$C_i$ : Heated contours length, [cm]
$C_p$ : Coolant specific heat, [J/kg·K]

### Subscripts:

$b$ : bulk
$f$ : film
$w$ : wall surface