IAEA NAPRO Coordinated Research Project : Heat Transfer and Pressure Drop Correlations for Sodium Cooled Systems

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In 2013 the International Atomic Energy Agency (IAEA) established a Coordinated Research Project (CRP) on "Sodium properties and safe operation of experimental facilities in support of the development and deployment of Sodium Cooled Fast Reactors", the so-called CRP-NAPRO project to be carried out in the time period of 2013–2017. This activity has the aim to establish a common database of sodium properties and related correlations, as well as other important sodium technology related issues, thus contributing to the enhanced safety of future sodium cooled systems. The CRP work package WP 1.2, under the leadership of Karlsruhe Institute of Technology (KIT), is focused on the collection and assessment of heat transfer and pressure drop (friction factor) correlations for sodium cooled systems. In the end result, this activity will lead to a recommendation of qualified correlations for conditions occurring in sodium systems, such as forced convection and natural convection for circular tubes, rod bundles, wire-wrapped tubes, etc., which will be published in the form of separate chapter(s) of a general handbook. This work is carried out by five participating organizations from IAEA Member States through the review and evaluation of the existing correlations and the development of recommendations for experts working on sodium cooled systems. The implemented methodology for WP 1.2 is described, as well as the heat transfer and pressure drop (friction factor) correlations collected and their classification. Major findings to date related to WP 1.2 are presented in this paper. The last section of the paper also includes preliminary conclusions, as well as a list of the main correlations used by the participating organizations when simulating sodium cooled fast reactors and other sodium cooled systems.

I. INTRODUCTION

A Coordinated Research Project (CRP)[1] on "Sodium properties and design and safe operation of experimental facilities in support of the development and deployment of Sodium Cooled Fast Reactors (SFR) - NAPRO" has been proposed by CEA and established in 2013 by IAEA.

The technical coordinator of this project is CEA. The scope of the CRP NAPRO is threefold:

1. gathering, expert assessment, and dissemination of consistent sodium property data to support SFR research, design, analysis, and development;
2. compilation, evaluation, development, and dissemination of best practices (design and operation) for sodium experimental facilities; and
3. compilation, evaluation, development, and dissemination of guidelines and rules for the safe operation of sodium experimental facilities.

The overall objective of the CRP is to support the Member States' SFR research programs by providing a consistent set of sodium property data, to specify property uncertainties and recommend correlations to be used as a common basis for the design, development, modeling, and simulation of advanced SFRs. A necessary condition towards achieving this objective is an extensive understanding of the existing available data, an evaluation of the existing data, the identification of data gaps, and the elaboration of recommendations for experimental programs required to close these data gaps. Supporting this necessary condition is the development of best practices for sodium experimental facility design and guidelines for the safe handling of sodium. The specific CRP research objectives are summarized in [1]. As elaborated by the CRP participants during the first Research Coordination Meeting (RCM), held in Vienna on 12-14 November 2013, the CRP is organized in three Work Packages (WPs) and then broken down in sub-WPs and specific Tasks. The WP1 (ANL being the technical coordinator of the WP) is dedicated to sodium physical properties, correlations for heat transfer and pressure drops, and chemical properties. The WP2 is focused on the development of harmonized guidelines for the design, construction, operation and decommissioning of sodium experimental facilities. The WP3 deals with safety aspects of sodium experimental facilities. This paper summarizes the status of work and presents preliminary results related to the sub-WP 1.2: Correlations for heat transfer and pressure drops.

II. WORK PACKAGE 1.2: STATUS OF WORK

The main objective of CRP NAPRO WP1 is the collection, assessment and dissemination of a comprehensive and uniform set of sodium physical properties, correlations for heat transfer and pressure drops, as well as chemical properties. More specifically, the sub-WP 1.2 deals with the collection and assessment of sodium related correlations as divided into two complementary tasks: the collection and assessment of heat transfer correlations and the collection and assessment of pressure drop (friction factor) correlations. Karlsruhe Institute of Technology (KIT) is the leading institution for the activities carried out under the sub-WP 1.2.

II.A. Participants

Under the support and coordination of the IAEA, nine research organizations (ANL, CEA, CIAE, CNEA, IGCAR, IPPE, JAEA, KIT, and NRG) from nine Member States (USA, France, China, Argentina, India, Russian Federation, Japan, Germany and the Netherlands) are participating in Work-Package 1, but only five participants (ANL, CEA, IGCAR, KIT and NRG) have been assigned with specific tasks within the sub-WP 1.2.

II.B. Methodology

The approach used by this sub-WP is somewhat different from the sodium physical and chemical properties review tasks. The whole process, to reach the final version of the chapter related to sub-WP 1.2 in the NAPRO deliverable (an IAEA-TECDOC document), is divided into three phases:

1) In the first phase, a matrix with the various conditions that can be met in any system dealing with sodium cooling in nuclear reactors was built. This conditions matrix includes global, as well as local conditions, different flow and thermal convection regimes and various pressure drops. Template tables were created to identify proposed heat transfer and pressure drop correlations, as well as the corresponding publications (original and review publications). The participants were requested to indicate the correlations that they know and also those they use and which are available in the open literature.
2) In the second phase, the completed table of existing conditions and the table of known correlations were already available. It was agreed that in case a particular condition is not very common and is neglected when modelling the sodium cooling system, or when a simplified approach is used, this fact needs to be mentioned as well. By comparing conditions and correlations tables, possible gaps or improvements needed for the existing correlations might be identified, thus forming a request for future investigations.
3) In the third phase, for every correlation mentioned in the compiled tables, participants wrote a description of each correlation with the characteristics mentioned previously, thus describing in detail the corresponding formulas. This write-up task was distributed equally among the five partners of the sub-WP 1.2. Complete text description and complete validated formulations of the correlations have been included as content of the final deliverable. However, no correlations graphs and/or comparison

graphs are foreseen, since they depend on the boundary conditions of the experiments and this is out of the scope of this sub-WP.

II.C. Correlations and references

During the whole activity of the sub-WP, collected were: 78 heat transfer correlations and 30 pressure drop (friction factor) correlations. Collected were also 127 references to the above mentioned correlations.

All collected heat transfer correlations are grouped as follows:

- Forced convection:
  - Correlations for a circular tube,
  - Correlations for a flat plate,
  - Correlations for parallel plates (flat duct),
  - Correlations for a concentric annuli,
  - Correlations for a horizontal cylinder,
  - Correlations for special cases,
  - Correlations for triangular rod bundles,
  - Correlations for square rod bundles,
  - Correlations for unspecified geometries;
- Natural convection:
  - Correlations for vertical plates,
  - Correlations for horizontal plates,
  - Correlations for inclined plates,
  - Correlations for cylinders,
  - Correlations for special cases;
- Correlations for sodium boiling (local conditions);
- Correlations for liquid sodium with impurities;
- Correlations for film and drop-wise condensation and evaporation.

All collected pressure drop (friction factor) correlations are grouped as follows:

- Single phase friction factor/pressure drop correlations:
  - Tubular section,
  - Rod bundle,
  - Wire-wrapped bundle,
  - Grid-spaced bundle;
- Two phase friction factor/pressure drop correlations:
  - Two-phase friction pressure drop
    - Tubular section
    - Rod bundles,
  - Two-phase local pressure drop correlations
    - Homogeneous model
    - Slip model,
  - Interfacial friction correlations.

II.D. Status of work

As of November 2015, all five participants (ANL, CEA, IGCAR, KIT and NRG) have already completed the collection of the existing heat transfer, as well as pressure drop (friction factor) correlations, thus forming a list of the corresponding references. Based on the list of correlations and a list of references, participants provided also the write-up of all collected heat transfer and pressure drop (friction factor) correlations for sodium cooled systems. Information is collected as well as to what correlations are used by the participants of this sub-WP themselves in their daily work when dealing with sodium cooled systems. This information is presented at the end of each section following the list of collected correlations. However, for the final sub-WP activity report it would be extremely useful to propose recommended correlation(s) for the most common conditions existing in sodium cooled reactor systems. This is the task for the coming months for this sub-WP and the participants are working now on this task.

As an example of the work done in this sub-WP, the summary tables of the collected heat transfer, as well as pressure drop (friction factor) correlations, corresponding to the most common analyzed conditions in sodium cooled systems are presented in detail in the following sections of this paper.

III. HEAT TRANSFER CORRELATIONS

Selected examples of the collected heat transfer correlations are presented in this section. Tables include the name of the authors, the year and reference of the publication, correlations themselves, as well as their range of validity.

III.A. Correlations for a circular tube (forced convection)

21 different correlations were collected for estimating forced convection heat transfer in a circular tube. They were published between 1930 and 2001. The summary is presented in Table I.

TABLE I. Correlations for a circular tube in forced convection

Dittus-Boelter (1930)[30]	$Nu = 0.023 Re^{0.8} Pr^{n}$ n=0.40 for heating; n=0.33 for cooling	Used for vapor phase only, and $Re \geq 10^5$ $0.6 \leq Pr \leq 160$
Lyon (1949)[32]	$Nu = 7 + 0.025 Pe^{0.8}$	$0 \leq Pr \leq 0.1$ $10^4 \leq Re \leq 5 \cdot 10^6$

Lyon (1951)[24]	$Nu = 7 + 0.025\left(\frac{Pe}{Pr_t}\right)^{0.8}$	$0 \le Pr_t \le 0.1$ $10^4 \le Re \le 5\cdot10^6$
Seban-Shimazaki (1951)[20]	$Nu = 5 + 0.025Pe^{0.8}$	$10^2 \le Pe \le 2\cdot10^4$
Stromquist (1953)[27]	$Nu = 3.6 + 0.018\,Pe^{0.8}$	$88<Pe<4\cdot10^3$
Lubarsky-Kaufman (1956)[31]	$Nu=0.625Pe^{0.4}$	$2.1\cdot10^3 \le Re \le 2.54\cdot10^5$ $Pr=0.0053$
Hartnett-Irvine (1957)[32]	$Nu = \frac{2}{3}Nu_{s,m} + 0.015\,Pe_m{}^{0.8}$	
Schleicher-Tribus (1957)[32]	$Nu_T = 4.8 + 0.015Re^{0.91}Pr^{1.21}$ (uniform wall temperature); $Nu_H = 6.3 + 0.016Re^{0.91}Pr^{1.21}$ (uniform wall heat flux)	$0 \le Pr \le 0.1$ $10^4 \le Re \le 5\cdot10^6$
Rohsenow (1960)[29]	$Nu = 6.7 + 0.0041(RePr)^{0.793}e^{41.8\cdot Pr}$	$5\cdot10^{-3}<Pr<5\cdot10^{-2}$ $Re>10^4$
Azer-Chao (1961)[32]	$Nu = 5 + 0.05\,Pr^{0.25}Pe^{0.77}$	
Andreevskii (1961)[32]	$Nu_f = 0.65\,Pe_f{}^{0.5}$	
Dwyer (1963)[32]	$Nu_H = 7 + 0.0025\left[Re\,Pr - \frac{1.82\,Re}{(\varepsilon_m/\nu)_{max}^{0.14}}\right]^{0.8}$ $(\varepsilon_m/\nu)_{max} = 0.037\,Re\sqrt{f}$ $\frac{1}{\sqrt{f}} = 1.7372\,\frac{Re}{1.964\,\ln Re - 3.8215}$	
Skupinski et al. (1965)[21]	$Nu=4.82+0.0185Pe^{0.827}$	$58<Pe<1.31\cdot10^4$
Dwyer (1966)[28]	$Nu = 7.0 + 0.025\left(Pe - \frac{1.82\,Re}{\left(\frac{\epsilon_M}{\nu}\right)_{max}^{1.4}}\right)^{0.8}$	
Notter-Sleicher (1972)[13]	$Nu_\infty = 5 + 0.016\,Re^a\,Pr^b$ $a=0.88-0.24/(4+Pr)$ $b=0.33+0.5e^{-0.6Pr}$	$10^4<Re<10^6$ $0.1<Pr<10^4$

Sleiher et. al. (1973)[22]	$Nu(x) = Nu_\infty\left(1 + \frac{2}{x/D}\right)$, x/D>4 $Nu_{ave} = Nu_\infty\left(1 + \frac{8}{L/D} + \frac{2}{L/D}\ln\frac{L/D}{4}\right)$; L/D>4 $Nu_\infty = 4.8 + 0.0156\,Pe^{0.85}\,Pr^{0.08}$ (uniform wall temperature); $Nu_\infty = 6.3 + 0.0167\,Pe^{0.85}\,Pr^{0.08}$ (uniform wall heat flux)	$2.6\cdot10^4<Re<3.02\cdot10^5$ $0.004<Pr<0.1$
Churchill-Bernstein (1977)[34]	$\overline{Nu} = \frac{0.62\,Re^{1/2}Pr^{1/3}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}}$ (laminar regime); $\overline{Nu} = 0.3 + \frac{0.62\,Re^{1/2}Pr^{1/3}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}}$ (intermediate regime) Pe>0.2, $Re<10^4$; $\overline{Nu} = \frac{1}{\left[0.8237-\ln\left(Pe^{2/3}\right)\right]^{1/4}}$ (creeping flow regime) Pe<0.2	
Chen-Chiou (1981)[32]	$Nu_T = 4.5 + 0.0156\,Re^{0.85}Pr^{0.86}$ (uniform wall temperature); $Nu_H = 5.6 + 0.0165\,Re^{0.85}Pr^{0.86}$ (uniform heat flux)	
Lee (1983)[32]	$Nu = 3.01Re^{0.0833}$	$5 \le Pe \le 1000$ $0.001 \le Pr \le 0.02$
Kakac et. al. (1987)[32]	$Nu = 3.3 + 0.02\,Pe_m^{0.8}$	$Pe_m>10^2$ $L/D_h>60$
Kirillov-Ushakov (2001)[23]	$Nu = A + 0.014\,Pe^{0.8}$ A=3 (with oxide films on the wall); A=4.5–5 (clean surfaces)	

Nomenclature of TABLE I:

Pe: Peclet number,
Pr: Prandtl number,
Re: Reynolds number,
D: pipe diameter,
L: length of pipe,
$Nu_{s,m}$: Nusselt number for slug flow,
ϵ_M: eddy diffusivity of momentum transfer,
ν: kinematic viscosity,
x: axial coordinate.

For a circular tube in forced convection, the heat transfer correlations being used by the participants are: Dittus-Boelter (1930; for vapor phase only), Lyon (1951), Lubarsky-Kaufman (1956), Skupinski et al. (1965), Notter-Sleicher (1972), Churchill-Bernstein (1977).

III.B. Correlations for triangular rod bundle (forced convection)

17 different correlations were collected for estimating heat transfer from a triangular rod bundle in forced convection regime. They were published between 1958 and 2009. The summary is presented in Table II.

TABLE II. Correlations for a triangular rod bundle in forced convection

Rickard et. al. (1958)[35]	$Nu=4.03+0.228Pe^{0.67}$	$2\cdot10^4<Re<2\cdot10^5$
Dwyer and Tu (1960)[11]	$Nu=0.93+10.81X-2.01X^2+0.0252X^{0.273}(\psi Pe)^{0.8}$	$10^2<Pe<10^4$ $1.375 \le X \le 2.2$
Friedland-Bonilla (1961)[11]	$Nu=7.0+3.8X^{1.52}+0.027X^{0.27}(\psi Pe)^{0.8}$	$0\le Pe\le 10^5$ $1.3\le X\le 10$
Borishanskii (1964)[38]	$Nu = 6 + 0.006\,Pe$	
Mareska-Dwyer (1964)[11]	$Nu=6.66+3.126X+1.184X^2+0.0155(\psi Pe)^{0.86}$	$70<Pe<10^4$ $13 < X < 3.0$ $\Psi = 1$
Subbotin et. al. (1965)[11]	$Nu=0.58*(De/do)^{0.55}Pe^{0.45}$	$80 \le Pe \le 4000$ $1.1 \le X \le 1.5$
Dwyer (1966)[34]	$[\,Nu\,]_{90\,deg} = 5.36 + 0.1974\,(\,Pe)_{v,max}{}^{0.682}$	
Borishanskii et al. (1969)[2]	$Nu=Nu_{lam}+Nu_{turb}$ $(200 \le Pe \le 2200)$; $Nu_{turb}=0.0174\{1-e^{[-6*(X-1)]}\}(Pe-200)^{0.9}$; $Nu_{lam}=24.15\log10(-8.12+12.76X-3.65X^2)$ $(Pe\le 200)$	
Dwyer-Berry (1970)[33]	$[\,\overline{Nu_t}\,]_{r.b.} = \frac{7}{8}[\,\overline{Nu_s}\,]_{r.b.} + 0.025\,(\bar{\psi}\,Pe_{r.b})^{0.8}$	
Gräber-Rieger (1972)[11]	$Nu=0.25+6.2X+[0.032*X-0.007]Pe^{(0.8-0.024X)})$	$110 \le Pe \le 4000$ $1.25 \le X \le 1.95$
Calamai et. al. (1974)[3]	$Nu = 4 + 0.16(X)^5 + 0.33(X)^{3.8}\left(\frac{Pe}{100}\right)^{0.86}$	$20\le Pe\le 10^3$
Kazimi-Carelli (1976)[19]	$Nu = 4 + 0.16(X)^5 + 0.33(X)^{3.8}\left(\frac{Pe}{100}\right)^{0.86}$	$1.1 \le X \le 1.4$ $10\le Pe\le 5\cdot10^3$
Kazimi-Carelli (1976)[19]	$Nu = [-16.15 + 24.96(X) - 8.55(X)^2]Pe^{0.3}$ for $150 \le Pe \le 10^3$; $Nu = 4.496[-16.15 + 24.96(X) - 8.55(X)^2]$ for $Pe \le 150$	
Foust (1976)[33]	$Nu = 6.66 + 3.126(X) + 1.184(X)^2 + 0.0155\,(\{1 - \frac{1.82}{Pr\,(^{\varepsilon_M}/_{\nu})_{max}^{1.4}}\}Pe)^{0.86}$	
Ushakov et. al. (1977)[11]	$Nu = 7.55X - \frac{20}{X^{13}} + \frac{0.041}{X^2}\left(1 - \frac{1}{\frac{X^{30}-1}{6} + \sqrt{1.15 + 1.24\varepsilon_6}}\right) * Pe^{0.56+0.19X-0.1X^{-80}}$ $0 < Pe \le 4000, 1.3 \le X \le 2.0$	
Zhukov et. al (1994)[25]	$Nu = 7.55\,X - 14\,(X)^{-5} + \frac{0.041}{(X)^2}Pe^{(0.56+0.19\,X)}$	
Mikityuk (2009)[11]	$Nu=0.047(1-e^{-3.8\,(X-1)})(Pe^{0.77}+250)$	$30 \le Pe \le 5000$ $1.1 \le X \le 1.95$

Nomenclature of TABLE II:

$[\,\overline{Nu_t}\,]_{r.b.}$: av. Nusselt number for turbulent flow through channels in general,

$[\,\overline{Nu_S}\,]_{r.b.}$: av. Nusselt number for in-line slug flow through unbaffled rod bundles, as a function of X:

X	$[\,\overline{Nu_S}\,]_{r.b.}$	X	$[\,\overline{Nu_S}\,]_{r.b.}$
1.05	3.76	1.40	14.65
1.07	5.77	1.50	15.52
1.10	8.29	1.60	16.36
1.20	12.18	1.80	18.01
1.30	13.66	2.00	19.81

$Pe_{r.b.}$: Peclet number for in-line turbulent flow through rod bundles,

De: hydraulic diameter,

do: rod diameter,

X: P/D ratio,

Ψ: Eddy diffusivity of heat / Eddy diffusivity of momentum.

For triangular rod bundle in forced convection, the following correlations are being used by the participants of the sub-WP: Borishanskii (1964), Calamai et al. (1974), Ushakov et al. (1977), Mikityuk (2009).

III.C. Correlations for square rod bundle (forced convection)

4 different correlations were collected for estimating heat transfer from a square rod bundle in forced convection regime. They were published between 1960 and 2009. The summary is presented in Table III.

TABLE III. Correlations for a square rod bundle in forced convection

Ushakov et. al.(1960)[33]	$Nu = 0.48 + 0.0133\, Pe^{0.7}$	
Zhukov et. al. (1994)[25]	$Nu = 7.55\, X - 20(X)^{-5} + \frac{0.0354}{(X)^2} Pe^{(0.56+0.204X)}$	$1.28 < X < 1.46$ $10^2 < Pe < 1.6 \cdot 10^3$
Zhukov et. al. (2002)[11]	$Nu = 7.55X - 14X^{-5} + 0.007Pe^{(0.64+0.246X)}$	$10 \le Pe \le 2.5 \cdot 10^3$ $1.2 \le X \le 1.5$
Mikityuk (2009)[11]	$Nu = 0.047(1 - e^{-3.8(X-1)})(Pe^{0.77} + 250)$	$30 \le Pe \le 5000$ $1.1 \le X \le 1.95$

Regarding heat transfer correlations for a square rod bundle in forced convection, correlation of Mikityuk (2009) is being used by the participants.

IV. PRESSURE DROP (FRICTION FACTOR) CORRELATIONS

Selected examples of the collected pressure drop (friction factor) correlations are presented hereafter.

IV.A. Correlations for wire-wrapped bundle (single phase flow)

10 different correlations were collected for estimating friction factor (pressure drop) in wire-wrapped bundles in single phase sodium flow. They were published between 1968 and 2010. The summary is presented in Table IV.

TABLE IV. Correlations for a wire-wrapped bundle (single phase flow)

Pontier (1968)[36]	$f = \Omega_0 e^r$ $\Omega_0 = 0.12Re^{-0.16}$ (roughness ~160 µm); $\Omega_0 = \left[-2\log\left[\frac{\varepsilon}{3.7D_h} + \left(\frac{6.81}{Re}\right)^{0.9}\right]\right]^{-2}$ (other roughness); $r = (1 + 4.6(X-1))\pi\frac{D}{H}$	$10^4 < Re < 10^5$ $15.7 < \frac{H}{d} < \infty$ $1.1 < \frac{d_m}{d} < 1.4$ $37 < N_{rod} < 331$ $0 < \pi\frac{d}{H} < 0.2$ $1.3 \cdot 10^{-4} < \varepsilon < 2 \cdot 10^{-4}$
Novendstern (1972)[14]	$f = \left(\frac{0.316}{Re^{0.25}} M\right)(X_1)^2 \left(\frac{D_{eb}}{D_{e1}}\right)$; $M = \left(\frac{1.034}{(X)^{0.124}} + \frac{29.7\,(X)^{6.94}\, Re^{0.086}}{(H/D)^{2.239}}\right)^{0.885}$	
Rehme (1973)[15]	$f = \left[\frac{64}{Re\sqrt{F}} + \frac{0.0816}{(Re\sqrt{F})^{0.133}}\right] F \frac{P_b}{P_{ass}}$ $F = (X)^{0.5} + \left[7.6\frac{d_m}{H}X^2\right]^{2.16}$	$10^3 < Re < 3 \cdot 10^5$ $8 < \frac{H}{d_m} < 50$ $1.1 < X < 1.42$ $7 < N_{rod} < 217$
Engel-Markley-Bishop (1979)[6]	$f = C_{fL}/Re$ ($Re < Re_L$); $f = \frac{C_{fL}}{Re}\sqrt{1-\phi} + \frac{C_{fT}}{Re^{0.25}}\sqrt{\phi}$ ($Re_L < Re < Re_T$); $f = C_{fT}/Re^{0.25}$ ($Re > Re_T$); $Re_L = 400$, $Re_T = 5000$ $\psi = \frac{Re-400}{4600}$, $C_{fT} = 0.55$ $C_{fL} = 110$ for $1.067 \le X \le 1.082$ $C_{fL} = \frac{320}{\sqrt{H}}(X)^{1.5}$ for X~1.2	$50 < Re < 10^5$ (fertile) $50 < Re < 400$ (fissile) $1.067 < X < 1.082$ (fertile) X ~1.2 (fissile) $19 < N_{rod} < 61$
Baxi-Dalle Donne (1981)[8]	$f = f_L = \frac{\left(\frac{T_w}{T_B}\right)\left(\frac{320}{\sqrt{H_w}}\right)X^{1.5}}{Re}$ (laminar region, Re<400); $f = f_T = \frac{0.316}{Re^{0.25}}\left(\frac{1.034}{X^{0.124}} + \frac{29.6\,(X)^{6.94}\, Re^{0.086}}{\left(\frac{H}{D}\right)^{2.239}}\right)^{0.88}$ (turbulent region, $Re > 5 \cdot 10^3$); $f = f_L\,(1-\Psi)^{0.5} + f_T\,\Psi^{0.5}$ $\Psi = \frac{(Re-400)}{4600}$ (transition region, $400 \le Re \le 5 \cdot 10^3$)	

Cheng-Todreas (1986)[5]	$f = C_{fL}/Re$ ($Re<Re_L$); $f = \frac{C_{fL}}{Re}(1-\phi)^{1/3} + \frac{C_{fT}}{Re^{0.18}}\phi^{1/3}$ ($Re_L<Re<Re_T$); $f = C_{fT}/Re^{0.18}$ ($Re>Re_T$); $Re_L = 300 \ x \ 10^{1.7(X-1)}$ $Re_T = 10^4 \ x \ 10^{1.7(X-1)}$ $\psi = \frac{\log\left(\frac{Re}{Re_L}\right)}{\log\left(\frac{Re_T}{Re_L}\right)}$ $C_{fL} = (-974.6 + 1612.0\,X - 598.5(X)^2)\left(\frac{H}{D}\right)^{0.06-0.085X}$ $C_{fT} = \left(0.8063 - 0.9022\,log\,\frac{H}{D} + 0.3526\left(log\,\frac{H}{D}\right)^2\right)X^{9.7}\left(\frac{H}{D}\right)^{1.78-2.0X}$	$50<Re<10^6$ $8<\frac{H}{d_m}<50$ (simplified correlation) $4<\frac{H}{d_m}<52$ (detailed correlation) $1.025<X<1.42$ (simplified), $1<X<1.42$ (detailed) $19<N_{rod}<217$
Zhukov et. al. (1986)[18]	$f = f_L = \frac{64}{Re}(0.407 + 2\,(X-1)^{0.5})\left(1 + \frac{17\,(X-1)}{\frac{H}{D}}\right)$ (laminar region, $Re<2\cdot10^3$); $f = f_T = \frac{0.21}{Re^{0.25}}(1 + (X-1)^{0.32})(1 + M\,(X-1)Re^{0.038})$ (turbulent region, $Re>6\cdot10^3$); $M = 30.3956 - 4.5911(H/D) + 0.24308(H/D)^2 - 0.0042955(H/D)^3$ $f = f_{Tr} = f_L\varepsilon + f_T(1-\varepsilon)$ (transition region, $2\cdot10^3\leq Re\leq6\cdot10^3$); $\varepsilon = 0.5\left(1 - \tanh\left(0.8\left(\frac{Re}{1450} - 1\right)\right)\right)$	
No-Kazimi et. al. (1987)[12]	$f_{f1} = f_L = \frac{32}{\sqrt{H}}X^{-1.5}\frac{D}{Re_l}$ ($Re_l \leq 400$); $f_{l1} = f_T = 0.316\,M/Re_l^{0.25}$ $M = \left(\frac{1.034}{(X)^{0.124}} + \frac{29.7\,(X)^{6.94}\,Re^{0.086}}{(H/D)^{2.239}}\right)^{0.885}$ ($Re_l \geq 2600$); $f_{l1} = f_{Tr} = f_T\sqrt{\Psi} + f_L\sqrt{1-\Psi}$, $\Psi = \frac{(Re_1-400)}{2200}$ ($400 \leq Re_l \leq 2600$)	

Sobolev (2006)[16]	$f = \left(1 + 600\left(\frac{D}{H}\right)^2\left(\frac{P_t}{D} - 1\right)\right) * \left(\frac{0.210}{Re^{0.25}}\left(1 + \left(\frac{P_t}{D} - 1\right)^{0.32}\right)\right)$
Kirillov et. al. (2010)4	$f = f_L = (64/Re)(0.407 + 2\,(X-1)^{0.5})\left(1 + \frac{17\,(X-1)}{H/D}\right)$ (laminar region, Re<400); $f = f_T = \left(\frac{0.21}{Re^{0.25}}\right)(1 + (X-1)^{0.32})\left(1 + 600\left(\frac{D}{H}\right)^2(X-1)\right)$ (turbulent region, $Re>5\cdot10^3$) Sobolev correlation; $f = f_{Tr} = f_L\,(1-\Psi)^{0.5} + f_T\,\Psi^{0.5}$ (transition region, $400\leq Re\leq5\cdot10^3$, where $\Psi = \frac{(Re-400)}{4600}$

Nomenclature of TABLE IV:

d_m: rod diameter + wire diameter,
P: rod pitch,
D: rod diameter,
D_{eb}: bundle equivalent D_h,
D_{e1}: equivalent D_h for bundles' central sub-channel,
H: wire pitch,
D_h: hydraulic diameter,
D_w: wire (spacer) diameter,
N_{rod}: rod number,
ε: roughness,
f: Darcy friction factor,
D_e: equivalent hydraulic diameter,
index $_b$ means bundle,
P_b: rod bundle and wire friction perimeter,
P_{ass}: total (with hexagonal box) friction perimeter,
P_t=D+1.0444D_w: rod pitch for wire-wrap configuration,
T_W: wall temperature in K,
T_B: coolant bulk temperature in K,
H_w: wire lead length in cm,
X: P/D ratio,
X_1: flow split parameter.

Regarding pressure drop (friction factor) correlations for a wire-wrapped bundle in single phase flow, the following correlations are being used by participants of the sub-WP: Pontier (1968), Rehme (1973), Cheng-Todreas detailed and simplified correlations (1986).

IV.B. Correlations for grid-spaced bundle (single phase flow)

5 different correlations were collected for estimating friction factor (pressure drop) in grid-spaced bundles in

single phase sodium flow. They were published between 1971 and 2010. The summary is presented in Table V.

TABLE V. Correlations for a grid-spaced bundle (single phase flow)

Voj et. al. (1971)[17]	$K = C_v \varepsilon^2 = \left(9.9 + \frac{2.2}{10^{-4} Re}\right) \varepsilon^2$
Rehme (1973)[15]	$\Delta p_{grid\ spacer} = C_v\ \varepsilon^2\ 0.5\ \rho\ v^2$ $C_v = min\left[3.5 + \frac{73.14}{Re^{0.264}} + \frac{2.79 \cdot 10^{10}}{Re^{2.79}}, \frac{2}{\varepsilon^2}\right]$ $\varepsilon = \frac{A_{grid\ spacer}}{A_{flow}}$
Savatteri et. al. (1986)[26]	$K = C_v \varepsilon^2 = \left(9 + \frac{3.8}{(10^{-4} Re)^{0.25}} + \frac{0.82}{(10^{-4} Re)^2}\right) \varepsilon^2$
Cevolani (1995)[26]	$K = C_v \varepsilon^2 = min\left[\varepsilon^2\ exp(7.69 - 0.9421\ ln(Re) + 0.0379\ ln^2(Re)), 2\right]$
Epiney et. al. (2010)[7]	$K = C_v \varepsilon^{0.2} = \left(1.104 + \frac{791.8}{Re^{0.748}} + \frac{3.348 \cdot 10^9}{Re^{5.652}}\right) \varepsilon^{0.2}$

Nomenclature of TABLE V:

ε: blockage factor of the grid spacer.

For a grid-spaced bundle in single phase flow, the pressure drop (friction factor) correlation of Rehme (1973) is being used by the participants.

IV.C. Correlations for tubular section (two-phase flow)

5 different correlations were collected for estimating friction factor (pressure drop) for a tubular section in two-phase sodium flow. They were published between 1949 and 1984. The summary is presented in Table VI.

TABLE VI. Correlations for a tubular section (two-phase flow)

Lockhart-Martinelli (1949)[9]	$X_{LM}^2 = \frac{Re_{gp}^m}{Re_{lp}^n} \frac{C_l}{C_g} \left(\frac{W_l}{W_g}\right)^2 \frac{\rho_g}{\rho_l}$ $Re_{gp} = \frac{4W_g}{\pi D_g \mu_g}, Re_{lp} = \frac{4W_l}{\pi D_l \mu_l}$	
Lottes-Flinn (1956)[10]	$\phi_l^2 = \frac{1}{(1-\alpha)^2}$	
Chen-Kalish (1970)[26]	$\ln\left(\frac{1}{\phi}\right) = -1.59 + 0.518 \ln(X_{LM}) - 0.0867\ (\ln(X_{LM}))^2$	
Kaiser et. al. (1974)[26]	$\phi_l = 8.2\ X_{LM}^{-0.55}$	
Kottowski-Savatteri (1984)[26]	$\log \phi = 0.1046\ (\log X_{LM})^2 - 0.5098 \log X_{LM} + 0.6252$	$0.07 < X_{LM} < 30$

Nomenclature of TABLE VI:

C_k: constant in Blasius equation for friction factor for the phase k,
W_k: weight rate of flow for phase k,
D_k: relative to the tube diameter and the flow conditions,
m and n are equal to 1 for viscous flow regime and to 0.2 for turbulent flow regime,
α: steam volume fraction,
X_{LM}: Lockhart-Martinelli parameter.

For pressure drop (friction factor) correlations/models for a tubular section in two-phase sodium flow, the following models are being used by the participants of the sub-WP: Lockhart-Martinelli (1949) and Lottes-Flinn (1956).

IV.D. Interfacial friction factor correlation (two-phase flow)

A correlation for the interfacial friction factor of thin annular flows in pipes was proposed by G.B. Wallis in 1969[37]. For a ratio a film thickness to diameter δ/D lower than 0.04 (corresponding to $\alpha \geq 0.8464$), experiments by Martinelli, Dukler, Sze Foo Chien and Charvonia cluster around the relationship:

$$(C_f)_i = 0.005\ \left(1 + 300\frac{\delta}{D}\right) = 0.005(1 + 150(1 - \sqrt{\alpha}) \quad (1)$$

where α is steam volume fraction.

Given the high liquid-to-vapor density ratio of sodium ($\rho_l/\rho_v \approx 2000$ at 1 atm.), the annular flow regimes covered by this correlation are encountered in most sodium boiling cases. However, one should note that it does not take into account the droplet entrainment and deposition phenomena that may occur at even higher α values.

Regarding pressure drop (friction factor) correlations/models for an interfacial friction in two-phase sodium flow, Wallis (1969) model is being used by the participants.

V. CONCLUSIONS

After about two years from the beginning of NAPRO project a big progress has been done in sub-WP 1.2 collecting, analyzing and preparing the final report about heat transfer and pressure drop (friction factor) correlations for sodium cooled systems.

From the work done so far, it is clear that it is extremely difficult to provide any real recommendation as to what heat transfer or pressure drop (friction factor) correlation should be used by an analyst in one or another situation or for one or another analyzed condition. What is possible at this point in time – is to state - what heat transfer or pressure drop (friction factor) correlations are used currently by the participants in their everyday work analyzing sodium cooled systems.

The following task is still to be completed: an internal revision of the current write-up extended also to other partners of the NAPRO project, not directly involved in sub-WP1.2 activities (such as JAEA, KAERI and IPPE), in order to identify missing information and to provide recommendations on how to improve the quality of the report, so that the final deliverable would be able to provide useful and up-to-date information to the end-reader of the foreseen IAEA-TECDOC. It should be mentioned here as well that the final deliverable of this sub-WP will also be reviewed by independent experts/reviewers from IAEA Member States.

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