



HAL
open science

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

E. Bubelis, S. Perez-Martin, S. Passerini, C. Gerardi, C. Grandy, S. Jayaraj,
F. Roelofs, C. Latge, A. Gerschenfeld, M. Anderhuber, et al.

► To cite this version:

E. Bubelis, S. Perez-Martin, S. Passerini, C. Gerardi, C. Grandy, et al.. IAEA NAPRO Coordinated Research Project : Heat Transfer and Pressure Drop Correlations for Sodium Cooled Systems. ICAPP 2016 - 2016 International Congress on Advances in Nuclear Power Plants, Apr 2016, San Francisco, United States. cea-02442356v1

HAL Id: cea-02442356

<https://cea.hal.science/cea-02442356v1>

Submitted on 16 Jan 2020 (v1), last revised 16 Jun 2020 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

E. Bubelis, S. Perez-Martin
Karlsruhe Institute of Technology
Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
Email: evaldas.bubelis@kit.edu, sara.martin@kit.edu

S. Passerini, C. Gerardi, C. Grandy
Argonne National Laboratory, Nuclear Engineering Division
9700 S. Cass Avenue, Building 208, Room A121, Argonne, IL 60439, USA
Email: stefano@anl.gov, cgerardi@anl.gov, cgrandy@anl.gov

S. Jayaraj, F. Roelofs
Nuclear Research and consultancy Group
Westerduinweg 3, PO Box 25, 1755 ZG Petten, The Netherlands
Email: jayaraju@nrg.eu, roelofs@nrg.eu

C. Latge, A. Gerschenfeld, M. Anderhuber, L. Cachon, L. Matteo
CEA, DEN, Cadarache, F-13108 Saint-Paul-lez-Durance, France.
Email: christian.latge@cea.fr, antoine.gerschenfeld@cea.fr,
marine.anderhuber@cea.fr, lionel.cachon@cea.fr, laura.matteo@cea.fr

S. Athmalingam, P. Selvaraj
IGCAR, Kalpakkam, 603102 Tamil Nadu, India
Email: athma@igcar.gov.in, pselva@igcar.gov.in

S. Monti
International Atomic Energy Agency
Wagramer Strasse 5, PO Box 100, A-1400 Vienna, Austria
Email: s.monti@iaea.org

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 included in WP 1.2 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 from WP 1.2, 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 established in 2013 under the leadership of the IAEA. The scope of the CRP NAPRO is threefold:

Commenté [AM1]: Some of us (Gerschenfeld, Anderhuber and Matteo) are from Saclay research center, not Cadarache

Commenté [AM2]: We could give their name in parentheses

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 WP 1 is dedicated to sodium physical properties, correlations for heat transfer and pressure drops, and chemical properties. The WP 2 is focused on the development of harmonized guidelines for the design, construction, operation and decommissioning of sodium experimental facilities. The WP 3 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 also-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 1.2.

II.C. Correlations and references

During the whole activity of sub-WP 1.2, 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 1.2 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 heat transfer from a circular tube in forced convection regime. 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	$Nu = 0.023Re^{0.8}Pr^n$ $n=0.40$ for heating; $n=0.33$ for cooling	$Re \geq 10^5$ $0.6 \leq Pr \leq 160$
Lyon (1949) ³²	$Nu = 7 + 0.025Pe^{0.8}$	$0 \leq Pr \leq 0.1$ $10^4 \leq Re \leq 5 \cdot 10^6$
Lyon (1951) ²⁴	$Nu = 7 + 0.025 \left(\frac{Pe}{Pr_t} \right)^{0.8}$	$0 \leq Pr_t \leq 0.1$ $10^4 \leq Re \leq 5 \cdot 10^6$
Seban-Shimazaki (1951) ²⁰	$Nu = 5 + 0.025Pe^{0.8}$	$10^2 \leq Pe \leq 2 \cdot 10^4$

Stromquist (1953) ²⁷	$Nu = 3.6 + 0.018 Pe^{0.8}$	$88 < Pe < 4 \cdot 10^3$
Lubarsky-Kaufman (1956) ³¹	$Nu = 0.625 Pe^{0.4}$	$2.1 \cdot 10^3 \leq Re \leq 2.54 \cdot 10^5$ $Pr = 0.0053$
Hartnett-Irvine (1957) ³²	$Nu = \frac{2}{3} Nu_{s,m} + 0.015 Pe_m^{0.8}$	
Schleicher-Tribus (1957) ³²	$Nu_T = 4.8 + 0.015 Re^{0.91} Pr^{1.21}$ (uniform wall temperature); $Nu_H = 6.3 + 0.016 Re^{0.91} Pr^{1.21}$ (uniform wall heat flux)	$0 \leq Pr \leq 0.1$ $10^4 \leq Re \leq 5 \cdot 10^6$
Rohsenow (1960) ²⁹	$Nu = 6.7 + 0.0041 (RePr)^{0.793} e^{41.8 Pr}$	$5 \cdot 10^{-3} < Pr < 5 \cdot 10^{-2}$ $Re > 10^4$
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	$Nu_H = 7 + 0.0025 \left[Re Pr - \frac{1.82 Re}{(\epsilon_M/v)_{max}^{0.14}} \right]^{0.8}$ $(\epsilon_M/v)_{max} = 0.037 Re \sqrt{f}$ $\frac{1}{\sqrt{f}} = 1.7372 \frac{Re}{1.964 \ln Re - 3.8215}$	
Skupinski et al. (1965) ²¹	$Nu = 4.82 + 0.0185 Pe^{0.827}$	$58 < Pe < 1.31 \cdot 10^4$
Dwyer (1966) ²⁸	$Nu = 7.0 + 0.025 \left(Pe - \frac{1.82 Re}{(\epsilon_M/v)_{max}^{1.4}} \right)^{0.8}$	
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	$2.6 \cdot 10^4 < Re < 3.02 \cdot 10^5$ $0.004 < Pr < 0.1$

	wall temperature); $Nu_\infty = 6.3 + 0.0167 Pe^{0.85} Pr^{0.08}$ (uniform wall heat flux)	
Churchill-Bernstein (1977) ³⁴	$\bar{Nu} = \frac{A Re^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr} \right)^{1/4} \right]^{1/4}}$ (laminar regime); $\bar{Nu} = 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr} \right)^{1/4} \right]^{1/4}}$ (intermediate regime) $Pe > 0.2, Re < 10^4$; $\bar{Nu} = \frac{1}{\left[0.8237 - \ln (Pe^{2/3}) \right]^{1/4}}$ (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	$Nu = 3.01 Re^{0.0833}$	$5 \leq Pe \leq 1000$ $0.001 \leq Pr \leq 0.02$
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)	

Commenté [AM3]: What is A ?

Nomenclature of TABLE I:

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

Commenté [AM4]: Add nomenclature of Re, Pe, Pr

For a circular tube in forced convection, the heat transfer correlations being used by the participants are: Dittus-Boelter (1930), 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	$Nu=4.03+0.228Pe^{0.67}$	$2 \cdot 10^4 < Re < 2 \cdot 10^5$
Dwyer and Tu (1960) ¹¹	$Nu=0.93+10.81X-2.01X^2+0.0252X^{0.273}(\psi Pe)^{0.8}$	$10^2 < Pe < 10^4$ $1.375 \leq X \leq 2.2$
Friedland-Bonilla (1961) ¹¹	$Nu=7.0+3.8X^{1.52}+0.027X^{0.27}(\psi Pe)^{0.8}$	$0 \leq Pe \leq 10^5$ $1.3 \leq X \leq 10$
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	$Nu=0.58*(De/do)^{0.55}Pe^{0.45}$	$80 \leq Pe \leq 4000$ $1.1 \leq X \leq 1.5$
Dwyer (1966) ³⁴	$[Nu]_{90 deg} = 5.36 + 0.1974 (Pe)_{v,max}^{0.682}$	
Borishanskii et al. (1969) ²	$Nu=Nu_{lam}+Nu_{turb}$ $(200 \leq Pe \leq 2200);$ $Nu_{turb}=0.0174\{1-e^{[-6*(X-1)]}\}(Pe-200)^{0.9};$ $Nu_{lam}=24.15\log_{10}(-8.12+12.76X-3.65X^2)$ $(Pe \leq 200)$	
Dwyer-Berry (1970) ³³	$[\overline{Nu}_t]_{r,b.} = \frac{7}{8}[\overline{Nu}_s]_{r,b.} + 0.025(\overline{\psi} Pe_{r,b})^{0.8}$	
Gräber-Rieger (1972) ¹¹	$Nu=0.25+6.2X+[0.032*X-0.007]Pe^{(0.8-0.024X)}$	$110 \leq Pe \leq 4000$ $1.25 \leq X \leq 1.95$
Calamai et al. (1974) ³	$Nu = 4 + 0.16 \left(\frac{P}{D}\right)^5 + 0.33 \left(\frac{P}{D}\right)^{3.8} \left(\frac{Pe}{100}\right)^{0.86}$	$20 \leq Pe \leq 10^3$
Kazimi-Carelli (1976) ¹⁹	$Nu = 4 + 0.16 \left(\frac{P}{D}\right)^5 + 0.33 \left(\frac{P}{D}\right)^{3.8} \left(\frac{Pe}{100}\right)^{0.86}$	$1.1 \leq P/D \leq 1.4$ $10 \leq Pe \leq 5 \cdot 10^3$

Kazimi-Carelli (1976) ¹⁹	$Nu = \left[-16.15 + 24.96 \left(\frac{P}{D}\right) - 8.55 \left(\frac{P}{D}\right)^2 \right] Pe^{0.3}$ for $150 \leq Pe \leq 10^3$; $Nu = 4.496 \left[-16.15 + 24.96 \left(\frac{P}{D}\right) - 8.55 \left(\frac{P}{D}\right)^2 \right]$ for $Pe \leq 150$	
Foust (1976) ³³	$Nu = 6.66 + 3.126 \left(\frac{P}{D}\right) + 1.184 \left(\frac{P}{D}\right)^2 + 0.0155 \left\{ 1 - \frac{1.82}{Pr \left(\frac{\epsilon_M}{\nu}\right)_{max}^{1.4}} \right\} Pe^{0.86}$	
Ushakov et al. (1977) ¹¹	$Nu = 7.55X - \frac{20}{X^{13}} + \frac{0.041}{X^2} \left(1 - \frac{1}{\frac{X^{30}-1}{6} + \sqrt{1.15 + 1.24\epsilon_e}} \right) * Pe^{0.56+0.19X-0.1X^{-80}}$ $0 < Pe \leq 4000, 1.3 \leq X \leq 2.0$	
Zhukov et al. (1994) ²⁵	$Nu = 7.55 \frac{P}{D} - 14 \left(\frac{P}{D}\right)^{-5} + \frac{0.041}{\left(\frac{P}{D}\right)^2} Pe^{(0.56+0.19\frac{P}{D})}$	
Mikityuk (2009) ¹¹	$Nu=0.047(1-e^{-3.8(X-1)})(Pe^{0.77}+250)$	$30 \leq Pe \leq 5000$ $1.1 \leq X \leq 1.95$

Commenté [AM6]: Couldn't use X for P/D ?
Ibid for some other correlations of this table

Nomenclature of TABLE II:

X: P/D ratio,
 Ψ : Eddy diffusivity of heat / Eddy diffusivity of momentum,
 De: hydraulic diameter,
 do: rod diameter,
 $[\overline{Nu}_t]_{r,b.}$: 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,
 $Pe_{r,b.}$: Peclet number for in-line turbulent flow through rod bundles.

For triangular rod bundle in forced convection, the following correlations are being used by the participants of sub-WP 1.2: Borishanskii (1964), Calamai et al. (1974), Ushakov et al. (1977), Mikityuk (2009).

Commenté [AM5]: Which correlation should we use for this Nu ?

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	$Nu = 7.55 \frac{P}{D} - 20 \left(\frac{P}{D}\right)^{-5} + \frac{0.0354}{\left(\frac{P}{D}\right)^2} Pe^{(0.56+0.204\frac{P}{D})}$	$1.28 < P/D < 1.46$ $10^2 < Pe < 1.6 \cdot 10^3$
Zhukov et al. (2002) ¹¹	$Nu = 7.55X - 14X^{-5} + 0.007Pe^{(0.64 + 0.246X)}$	$10 \leq Pe \leq 2.5 \cdot 10^3$ $1.2 \leq X \leq 1.5$
Mikityuk (2009) ¹¹	$Nu = 0.047(1 - e^{-3.8(X-1)}) (Pe^{0.77} + 250)$	$30 \leq Pe \leq 5000$ $1.1 \leq X \leq 1.95$

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	$f = \Omega_0 e^{\tau}$ $\Omega_0 = 0.12 Re^{-0.16}$ (roughness ~160 μm); $\Omega_0 = \left[-2 \log \left[\frac{\varepsilon}{3.7 D_h} + \right. \right.$	$10^4 < Re < 10^5$ $15.7 < \frac{H}{d} < \infty$ $1.1 < \frac{d_m}{d} < 1.4$ $37 < N_{rod} < 331$ $0 < \pi \frac{d}{H} < 0.2$
------------------------------	--	---

	$\left(\frac{6.81}{Re}\right)^{0.91} \left]^{-2}$ (other roughness); $r = \left(1 + 4.6 \left(\frac{P}{d} - 1\right)\right) \pi \frac{d}{H}$	$1.3 \cdot 10^{-4} < \varepsilon < 2 \cdot 10^{-4}$
Novendstern (1972) ¹⁴	$f = (f_1)(X_1)^2 \left(\frac{D_{eb}}{D_{e1}}\right)$	
Rehme (1973) ¹⁵	$f = \left[\frac{64}{Re\sqrt{F}} + \frac{0.0816}{(Re\sqrt{F})^{0.1333}} \right] F \frac{P_b}{P_{ass}}$ $F = \left(\frac{P}{d}\right)^{0.5} + \left[7.6 \frac{d_m}{H} \left(\frac{P}{d}\right)\right]^{2.16}$	$10^3 < Re < 3 \cdot 10^5$ $8 < \frac{H}{d_m} < 50$ $1.1 < \frac{P}{d} < 1.42$ $7 < N_{rod} < 217$
	$f = C_{fL}/Re$ ($Re < Re_L$); $f = \frac{C_{fL}}{Re} \sqrt{1 - \psi} + \frac{C_{fT}}{Re^{0.25}} \sqrt{\psi}$ ($Re_L < Re < Re_T$); $f = C_{fT}/Re^{0.25}$ ($Re > Re_T$); $Re_L = 400, Re_T = 5000$ $\psi = \frac{Re - 400}{4600}, C_{fT} = 0.55$ $C_{fL} = 110$ for $1.067 \leq p/d \leq 1.082$	$50 < Re < 10^5$ (fertile) $50 < Re < 400$ (fissile) $1.067 < \frac{P}{d} < 1.082$ (fertile) $\frac{P}{d} \sim 1.2$ (fissile) $19 < N_{rod} < 61$
Engel-Markley-Bishop (1979) ⁶	$C_{fL} = \frac{320}{\sqrt{H}} \left(\frac{p}{d}\right)^{1.5}$ for $p/d \sim 1.2$	
Baxi-Dalle Donne (1981) ⁸	$f = f_L = \frac{\left(\frac{T_w}{T_B}\right) \left(\frac{320}{\sqrt{H_w}}\right) (P/D)^{1.5}}{Re}$ (laminar region, $Re < 400$); $f = f_T = \frac{0.316}{Re^{0.25}} \left(\frac{1.034}{\left(\frac{P}{D}\right)^{0.124}} + \frac{29.6 \left(\frac{P}{D}\right)^{6.94} Re^{0.086}}{\left(\frac{H}{D}\right)^{2.239}}\right)^{0.885}$ (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, $400 \leq Re \leq 5 \cdot 10^3$)	
Cheng-Todreas (1986) ⁵	$f = C_{fL}/Re$ ($Re < Re_L$); $f = \frac{C_{fL}}{Re} (1 - \psi)^{1/3} + \frac{C_{fT}}{Re^{0.18}} \psi^{1/3}$ ($Re_L < Re < Re_T$); $f = C_{fT}/Re^{0.18}$ ($Re > Re_T$); $Re_L = 300 \times 10^{1.7} \left(\frac{P}{D} - 1\right)$	$50 < Re < 10^6$ $8 < \frac{H}{d_m} < 50$ (simplified correlation) $4 < \frac{H}{d_m} < 52$ (detailed correlation) $1.025 < \frac{P}{d} < 1.42$

Commenté [AM10]: X ?

Commenté [AM11]: What is X₁? D_{eb}? D_{e1}? f₁?

Mis en forme : Police : Times New Roman, Non Italique

Commenté [AM7]: X ?

Commenté [AM8]: Same correlation as for triangular rod bundle...

Commenté [AM9]: What is r ?

Mis en forme : Police : Times New Roman, Non Italique

	$Re_r = 10^4 \times 10^{1.7 \left(\frac{P}{D} - 1\right)} \psi = \frac{\log\left(\frac{Re}{Re_L}\right)}{\log\left(\frac{Re_r}{Re_L}\right)}$ <p>(simplified), $1 < \frac{P}{d} < 1.42$ (detailed) $19 < N_{rod} < 217$</p> $C_{fL} = \left(-974.6 + 1612.0 \frac{P}{D} - 598.5 \left(\frac{P}{D}\right)^2\right) \left(\frac{H}{D}\right)^{0.06 - 0.085 \frac{P}{D}}$ $C_{fT} = \left(0.8063 - 0.9022 \log \frac{H}{D} + 0.3526 \left(\log \frac{H}{D}\right)^2\right) \left(\frac{P}{D}\right)^{0.97} \left(\frac{H}{D}\right)^{1.78}$
Zhukov et al. (1986) ¹⁸	$f = f_L = \frac{64}{Re} \left(0.407 + 2 \left(\frac{P}{D} - 1\right)^{0.5}\right) \left(1 + \frac{17 \left(\frac{P}{D} - 1\right)}{D}\right)$ <p>(laminar region, $Re < 2 \cdot 10^3$);</p> $f = f_r = \frac{0.21}{Re^{0.25}} \left(1 + \left(\frac{P}{D} - 1\right)^{0.32}\right) \left(1 + M \left(\frac{P}{D} - 1\right) Re^{0.039}\right)$ <p>(turbulent region, $Re > 6 \cdot 10^3$);</p> $f = f_{Tr} = f_L \varepsilon + f_r (1 - \varepsilon)$ <p>(transition region, $2 \cdot 10^3 \leq Re \leq 6 \cdot 10^3$);</p> $\varepsilon = 0.5 \left(1 - \tanh \left(0.8 \left(\frac{Re}{1450} - 1\right)\right)\right)$
No-Kazimi et al. (1987) ¹²	$f_{f1} = f_L = \frac{32}{\sqrt{H}} \left(\frac{D}{P}\right)^{1.5} \frac{D}{Re_l}$ <p>($Re_l \leq 400$);</p> $f_{f1} = f_r = 0.316 M / Re_l^{0.25}$ $M = \left(\frac{1.034}{\left(\frac{P}{D}\right)^{0.124}} + \frac{29.7 \left(\frac{P}{D}\right)^{6.94} Re^{0.086}}{\left(\frac{H}{D}\right)^{2.239}}\right)^{0.885}$ <p>($Re_l \geq 2600$);</p> $f_{f1} = f_{Tr} = f_r \sqrt{\Psi} + f_L \sqrt{1 - \Psi}$ $\Psi = \frac{(Re_l - 400)}{2200} \quad (400 \leq Re_l \leq 2600)$
Sobolev (2006) ¹⁶	$f = \left(1 + 600 \left(\frac{D_r}{H}\right)^2 \left(\frac{P_t}{D_r} - 1\right)\right) * \left(\frac{0.210}{Re^{0.25}} \left(1 + \left(\frac{P_t}{D_r} - 1\right)^{0.32}\right)\right)$
	$f = f_L = \left(\frac{64}{Re}\right) (0.407 + 2 \left(\frac{P}{D} - 1\right)^{0.5}) \left(1 + \frac{17 \left(\frac{P}{D} - 1\right)}{D}\right)$

	$\frac{17 \left(\frac{P}{D} - 1\right)}{H/D}$ <p>(laminar region, $Re < 400$);</p> $f = f_r = \left(\frac{0.21}{Re^{0.25}}\right) \left(1 + \left(\frac{P}{D} - 1\right)^{0.32}\right) \left(1 + 600 \left(\frac{D}{H}\right)^2 \left(\frac{P}{D} - 1\right)\right)$ <p>(turbulent region, $Re > 5 \cdot 10^3$)</p> <p>Sobolev correlation;</p> $f = f_{Tr} = f_L (1 - \Psi)^{0.5} + f_r \Psi^{0.5}$ <p>(transition region, $400 \leq Re \leq 5 \cdot 10^3$, where $\Psi = \frac{(Re - 400)}{4600}$)</p>
Kirillov et al. (2010) ⁴	

Nomenclature of TABLE IV:

dm: rod diameter + wire diameter,
 p: rod pitch,
 d: rod diameter,
 H: wire pitch,
 D_h: hydraulic 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,
 T_w: wall temperature in K,
 T_B: coolant bulk temperature in K,
 H_w: wire lead length in cm.

Regarding pressure drop (friction factor) correlations for a wire-wrapped bundle in single phase flow, the following correlations are being used by participants of sub-WP 1.2: 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	$\Delta p_{grid\ spacer} = C_v \varepsilon^2 0.5 \rho v^2$ $C_v = \min \left[3.5 + \frac{73.14}{Re^{0.264}} + \frac{2.79 \cdot 10^{10}}{Re^{2.79}}, \frac{2}{\varepsilon^2}\right]$ $\varepsilon = \frac{A_{grid\ spacer}}{A_{flow}}$

Commenté [AM15]: Need to add d_m at the nomenclature

Commenté [AM12]: What is M ?

Commenté [AM13]: What is M ?

Commenté [AM14]: What are P_t and D_r ?

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	$X_{LM}^2 = \frac{Re_{gp}^m C_1}{Re_{lp}^n C_g} \left(\frac{W_1}{W_g} \right)^2 \frac{\rho_g}{\rho_l}$ $Re_{gp} = \frac{4W_g}{\pi D_g \mu_g}, Re_{lp} = \frac{4W_l}{\pi D_l \mu_l}$
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 sub-WP 1.2: 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 1969³⁷. 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 within sub-WP 1.2, 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 of this sub-WP in their everyday work analyzing sodium cooled systems.

The following task is still to be completed in sub-WP 1.2: 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.

ACKNOWLEDGMENTS

The authors wish to thank the International Atomic Energy Agency for the support, guidance and leadership on the NAPRO Coordinated Research Project.

REFERENCES

1. S. MONTI, C. Latge, B. Long, O. E. Azpitarte, P. Chellapandi, R. Stieglitz, S. Eckert, H. Ohira, J. Lee, F. Roelofs, E. Marinenko, C. Grandy, "A New IAEA Coordinated Research Project on Sodium Properties and Safe Operation of Experimental Facilities in Support of the Development and Deployment of Sodium-Cooled Fast Reactors", ICAPP 2014, 474-481, (2013).
2. V.M. BORISHANSKII, M.A. Gotovskii, E.V. Firsova, "Heat transfer to liquid metals in longitudinally wetted bundles of rods", *Atomnaya Energiya* 27 (6), p. 549-552 (1969).
3. G. J. CALAMAI, R. D. Coffield, J. L. Jossens, J. L. Kerian, J. V. Miller, E. H. Novendstern, G. H. Ursim, H. West, P. J. Wood, "Steady State Thermal and Hydraulic Characteristics of the FFTF Fuel Assemblies", Westinghouse Electric Corp. FRT-1582, Sunnyvale, CA. (1974).
4. S.K. CHEN, N.E. Todreas, N.T. Nguyen, "Evaluation of existing correlations for the prediction of pressure drop in wire-wrapped hexagonal array pin bundles", *Nuclear Engineering and Design* 267, p. 109-131 (2014).
5. S.K. CHENG and N.E. TODREAS, "Hydrodynamic models and correlations for bare and wire wrapped hexagonal rod bundles - bundle friction factors, subchannel friction factors and mixing parameters", *Nuclear Engineering and Design* 92, p. 227-251 (1986).
6. F.C. ENGEL, R.A. Markley, A.A. Bishop, "Laminar, transition, and turbulent parallel flow pressure drop across wire-wrap-spaced rod bundles", *Nuclear Science and Engineering* 69, p. 290-296 (1979).
7. A. EPINEY, K. Mikityuk, R. Chawla, "TRACE qualification via analysis of the EIR gas-loop experiments with smooth rods", *Annals of Nuclear Energy* 37, p. 875-887 (2010).
8. C.B. BAXI and M. DALLE DONNE, *Helium cooled systems. The gas-cooled fast breeder reactor*. H. Fenech, Ed., Heat Transfer and Fluid Flow in Nuclear Systems, Pergamon Press Inc., p. 407-462 (1981).
9. R.W. LOCKHART and R.C. MARTINELLI, "Proposed correlation of data for isothermal two-phase, two-component flow in pipes", *Chemical Engineering Progress* 45 (1), ISBN 0-89448-037-5, p. 39-48 (1949).
10. P.A. LOTTES and W.S. FLINN, "A method of analysis of natural circulation boiling systems", *Nuclear Science and Engineering* 1, p. 461-476 (1956).
11. K. MIKITYUK, "Heat transfer to liquid metal: review of data and correlations for tube bundles", *Nuclear Engineering and Design* 239, p. 680-687 (2009).
12. H.C. NO and M.S. KAZIMI, "An investigation of the physical foundations of two-fluid representation of sodium boiling in the liquid-metal fast breeder reactor", *Nuclear Science and Engineering* 97, p. 327-343 (1987).
13. R.H. NOTTER and C.A. SLEICHER, "A Solution to the Turbulent Graetz Problem - III. Fully Developed and Entry Region Heat Transfer Rates", *Chem. Eng. Sci.* 27, p. 2073-2093 (1972).
14. E. H. NOVENDSTERN, "Turbulent flow pressure drop model for fuel rod assemblies utilizing a helical wire-wrap spacer system", *Nuclear Engineering and Design* 22, p. 19-27 (1972).
15. K. REHME, "Pressure drop correlations for fuel element spacers", *Nuclear Technology* 17, p. 15-23 (1973).
16. V. SOBOLEV, "Fuel rod and assembly proposal for XT-ADS pre-design", Coordination meeting of WP1 & WP2 of DMI IP EUROTRANS, Bologna (2006).
17. P. VOJ, D. Markfort, E. Ruppert, "A thermal-hydraulic analysis for fuel elements with liquid-metal cooling", Proceedings of Int. Conf. of Heat and Mass Transfer, p. 179-193 (1971).
18. A.V. ZHUKOV, A.P. Sorokin, P.A. Titov, P.A. Ushakov, "Analysis of the fast reactors fuel-rod bundle flow resistance", *Atomnaya Energiya* 60 (5), p. 317-321 (1986).

19. M.S. KAZIMI and M.D. CARELLI, "Heat Transfer Correlation for Analysis of CRBRP Assemblies", Westinghouse, CRBRP-ARD-0034 (1976).
20. R.A. SEBAN and T.T. SHIMAZAKI, "Heat transfer to a fluid flowing turbulently in a smooth pipe with walls at constant temperature", Transactions of the ASME, Vol. 73, p. 803-809 (1951).
21. E. SKUPINSKI, J. Tortel, L. Vautre, "Determination des coefficients de convection d'un Alliage sodium-potassium Dans un Tube Circulaire", *Int. J. Heat Mass Transfer* 8, p. 937-951 (1965).
22. C.A. SLEICHER, A.S. Awad, R.H. Notter, "Temperature and eddy diffusivity profiles in NaK", *Int. J. Heat Mass Transfer* 16, p. 1565-1575 (1973).
23. P.L. KIRILLOV and P.A. USHAKOV, "Heat transfer to liquid metals: specific features, methods of investigation, and main relationships", *Thermal Eng.* 48 (1), p. 50-59 (2001).
24. R.N. LYON, "Liquid metal heat transfer coefficients", *Chem. Eng. Progr.* 47 (2), p. 75-79 (1951).
25. E.O. ADAMOV and V.V. ORLOV, "Naturally safe lead-cooled fast reactor for large-scale nuclear power", Dollezhal RDIPE, Moscow (2001).
26. A. CHENU, K. Mikityuk, R. Chawla, "Pressure drop modeling and comparisons with experiments for single- and two-phase sodium flow", *Nucl. Eng. Des.* 241, p. 3898-3909 (2011).
27. X. CHENG and N.I. TAK, "Investigation on turbulent heat transfer to lead-bismuth eutectic flows in circular tubes for nuclear applications", *Nucl. Eng. Des.* 236, p. 385-393 (2006).
28. O.E. DWYER, "Recent developments in liquid-metal heat transfer", *Atom. Energy Rev.* 4 (1), p. 3-92 (1966).
29. W.M. ROHSENOW and H.Y. CHOI, *Heat, Mass and Momentum Transfer*, Prentice-Hall, Inc. (1961).
30. F.W. DITTUS and L.M.K. BOELTER, *Heat transfer in automobile radiators of the tubular type*, Pubs. Eng. 2, 443, Univ. Calif. Berkeley (1930).
31. B. LUBARSKY and S.J. KAUFMAN, "Review of experimental investigations of liquid-metal heat transfer", NACA Rept. 1270 (1956).
32. S. KAKAC, R.K. Shah, W. Aung, *Handbook of Single-Phase Convective Heat Transfer*, John Wiley & Sons, Inc. (1987).
33. Y.S. TANG, R.D. Coffield, R.A. Markley, "Thermal Analysis of Liquid-Metal Fast Breeder Reactors", ANS (1978).
34. S.W. CHURCHILL and M. BERNSTEIN, "A Correlating Equation for Forced Convection From Gases and Liquids to a Circular Cylinder in Crossflow", *Journal of Heat Transfer* 99, p. 300-306 (1977).
35. C.L. RICKARD, O.E. Dwyer, D. Dropkin, "Heat transfer rates to cross flowing mercury in a staggered tube bank", *Trans. ASME* 80, p. 646 (1958).
36. L. PONTIER and J. COMBE, "Etude des pertes de charge dans les faisceaux d'aiguilles", CEA DRP/SEMTR/CAD R. 555 (1968).
37. G.B. WALLIS, *One dimensional Two-phase Flow*, MC Graw-Hill, New York (1969).
38. V.M. BORISHANSKII and E.V. FIRSOVA, "Heat exchange in separated bundles of rods with metallic sodium flowing longitudinally", Translated from *Atomnaya Energiya*, Vol. 16, No. 5, p. 457-458 (1964).