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Assessment of thermal–hydraulic correlations for narrow rectangular channels with high heat flux and coolant velocity

Alberto Ghione [a,b,*], Brigitte Noel [a], Paolo Vinai [b], Christophe Demazière [b]

[a] Commissariat à l'Énergie Atomique et aux énergies alternatives, CEA, DEN/DM2S/STMF/LATF, 17 rue des Martyrs, Grenoble, France
[b] Chalmers University of Technology, Division of Subatomic and Plasma Physics, Department of Physics, Gothenburg, Sweden

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A B S T R A C T

The focus of the paper is on the evaluation of the correlations for predicting single-phase friction, single- and two-phase forced convection heat transfer coefficients in rectangular narrow channels, where the wall heat flux and the coolant flow can reach relatively high values.

For this purpose, several correlations are reviewed and assessed against the SULTAN-JHR experiments. These tests were performed at CEA-Grenoble with upward water flow in two vertical uniformly heated narrow rectangular channels with gap of 1.51 and 2.16 mm. The experimental conditions range between 0.2 and 0.9 MPa for the pressure; 0.5–18 m/s for the coolant velocity and between 0.5 and 7.5 MW/m^2 for the heat flux.

The use of an appropriate turbulent friction factor leads to good comparison with the experimental data.

The analysis of the single-phase turbulent heat transfer coefficient shows that the standard correlations (e.g. Dittus–Boelter) significantly under-estimate the heat transfer coefficient, especially at high Reynolds number. Therefore, new best-fitting correlations are derived. It is also observed that a reduction in gap size may lead to the enhancement of the heat transfer.

The heat transfer is also under-estimated in two-phase flow if standard correlations (e.g. Jens–Lottes) are employed; however, good comparison with the experimental data are obtained with more appropriate models for fully developed boiling, such as the Forster–Greif correlation.

The global accuracy associated to these correlations is also quantified in a rigorous manner.

1. Introduction

Narrow rectangular channels can be an attractive solution for several engineering applications that require high-performance cooling capabilities within compact volumes, such as research nuclear reactors, electromagnets, and electronic equipment. In order to use this type of channels in an efficient and reliable manner, accurate simulation models based on appropriate correlations for single- and two-phase flows and heat transfer are needed.

The case of heated vertical narrow channels, with an upward forced flow of water, is of particular interest for nuclear research reactors, where high power densities are produced in small core volumes. Several studies are available from the open literature (e.g. [1–3]), however the data are often limited to relatively small ranges of conditions, with relatively low heat and mass fluxes. In this paper, selected correlations for single-phase turbulent friction factor, for the single-phase turbulent heat transfer coefficient, and for the wall superheat under fully developed boiling (FDB) are evaluated over wider conditions. In particular, the assessment relies on experiments with high heat flux at the wall (up to 7.5 MW/m^2) and with high velocities of the coolant flow (up to 18 m/s), in channels with gaps of 1.509 and 2.161 mm. These experiments were carried out in connection to the design of the Jules Horowitz Reactor [4], at CEA-Grenoble, within the SULTAN-JHR campaign [5,6].

Preliminary analyses of the SULTAN-JHR data were presented in [6–8]. The current study improves and completes the previous results; identifies suitable correlations that can be applied to the range of conditions of interest; and, also, includes a rigorous estimation of the accuracy associated to those correlations. Several methods for the quantification of the uncertainty are applied and compared, so that reliable quantitative information can be obtained.

* Corresponding author at: Chalmers University of Technology, Division of Subatomic and Plasma Physics, Department of Physics, Gothenburg, Sweden.

E-mail addresses: ghione@chalmers.se (A. Ghione), brigitte.noel@cea.fr (B. Noel), vinai@chalmers.se (P. Vinai), demaz@chalmers.se (C. Demazière).

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Nomenclature

A	flow area m^2
c_p	specific heat capacity J/kg/K
D_b	bubble diameter m
D_h	hydraulic diameter $D_h = \frac{4A}{P_w}$ m
f	friction factor
g	acceleration of gravity $g = 9.8066$ m/s^2
G	mass flux $G = \frac{\dot{m}}{A}$ kg/m^2/s
h	heat transfer coefficient W/m^2/K
i	specific enthalpy J/kg
i_{lg}	latent heat J/kg
k	thermal conductivity W/m/K
$\dot{m}$	mass flow rate kg/s
Nu	Nusselt number $Nu = \frac{hD_h}{k}$
p	pressure Pa
p_{crit}	critical pressure (for water: $p_{crit} = 22.064 \cdot 10^6$) Pa
Δp	pressure drop Pa
Pr	Prandtl number $Pr = \frac{\mu c_p}{k}$
P_h	heated perimeter m
P_r	reduced pressure $P_r = \frac{p}{p_{crit}}$
P_w	wet perimeter m
Re	Reynolds number $Re = \frac{GD_h}{\mu}$
T	temperature °C
ΔT	temperature difference °C
x	thermodynamic steam quality
z	axial distance m

Greek symbols

μ	dynamic viscosity kg/m/s
ρ	density kg/m^3
σ	surface tension kg/s^2
ϕ	heat flux W/m^2

Subscripts

g	gas
l	liquid
sat	saturation
sub	subcooled
w	wall

The paper is organized as follows: in the next section a brief description of the SULTAN-JHR experiments is given; in Section 3 the modeling of the experiments and the methods used for the quantification of the accuracy of the correlations are explained; in Sections 4,5 and 6 the results for the single-phase turbulent friction factor, the single-phase turbulent heat transfer coefficient, and the wall superheat under fully developed boiling are presented, respectively; in Section 7 conclusions are drawn.

2. The Sultan-JHR experiments

The SULTAN-JHR experimental campaign was conducted at CEA Grenoble (France) during the years 2001–2008, with the objective of providing a reliable set of data for system code validation. The test section consisted of a narrow vertical rectangular channel that is uniformly electrically heated and where demineralized and degassed water flows upward.

About 300 steady-state tests were carried out. The experimental conditions, which are summarized in Table 1, were selected to be representative of the ones in the Jules Horowitz Reactor.

2.1. Test section geometry

Two different test sections were used: Section 3 (SE3) and Section 4 (SE4) with channel gap equal to 1.509 and 2.161 mm, respectively. As shown in Fig. 1, the channel is delimited by two Inconel-600 plates that are approximatively 1 mm thick. The power was supplied via direct electrical heating of the plates. The extremities of the walls are thinner in order to avoid heat concentration effects that may cause early boiling and potential thermal crisis at the corners.

Table 1
SULTAN-JHR experimental conditions.

Outlet pressure [MPa]	0.2–0.9
Inlet water temperature [°C]	25–160
Mass flow rate [kg/s]	0.05–2.0
Flow velocity [m/s]	0.5–18
Uniform heat flux [MW/m^2]	0.5–7.5

The test section is encapsulated in an electrical mica-based insulation (*Cogetherm*®) and two pressure steel plates which maintain the channel gap and geometry reasonably constant during all tests. In fact, the gap size was proven to be quite constant along the channel, by comparing the different pressure drops measured in the isothermal tests. On the external side, the test section is thermally insulated with 200 mm of rock wool so that heat losses could be reduced. The dimensions of the test section with the associated nomenclature are reported in Table 2.

The axial geometry and instrumentation layout of the test section is shown in Fig. 2. The central part of the channel is heated with an approximately uniform heat flux, while two 70 mm-long adiabatic zones are present at the extremities of the test section. A smooth entrance in the test section was used in order to minimize the entrance effects.

2.2. Instrumentation

Several quantities were measured during the experiments, including the mass flow rate, the electrical voltage and current, the water and dry wall temperatures, the absolute pressures and the pressure drops along the channel. The signals from the sensors were integrated over a 20 ms time range and the final measurements were obtained as an average of 100 acquisitions, in order to increase the stability and reliability of the measurements. The voltage ΔV between the pressure taps P3 and P6 and the electrical current I were measured, so that the electrical power supplied to the test section could be estimated according to the formula $P = \Delta V \times I$. The water temperatures at the inlet (TE1 and TE2) and at the outlet (TS1 and TS2) were measured with a platinum probe.

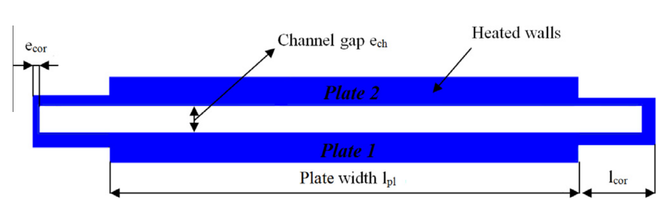

Fig. 1. Geometry of the SULTAN-JHR test section (top view).