Nuclear Engineering and Design 335 (2018) 356–373

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

The upgraded Cheng and Todreas correlation for pressure drop in hexagonal wire-wrapped rod bundles

S.K. Chen[a,*,1], Y.M. Chen[a], N.E. Todreas[b]

[a] Institute of Nuclear Engineering and Science, National Tsing-Hua University, Hsinchu 30013, Taiwan
[b] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

ARTICLE INFO

Keywords:
Wire-wrapped
Pressure drop
Friction factor
Correlation

ABSTRACT

The Cheng and Todreas (detailed) correlation (CTD) for wire-wrapped rod bundle friction factor published in 1986 has been identified in Chen et al. (2014) as the most used correlation for design and safety analyses for the Generation IV Sodium Fast Reactor(SFR). Since its publication in 1986, sixteen additional wire wrapped fuel bundle experiments have been performed worldwide providing data to supplement regions of minimal data in the bundle test data base. Based on this valuable new data, the CTD correlation has been refined in the following three aspects and renamed the Upgraded CTD (UCTD) Correlation.

1. The laminar to transition boundary Reynolds value has been significantly reduced. As well, a new laminar boundary equation is adopted which gives much lower value for the laminar boundary (Re_{bL}) as a function of P/D.
2. The transition region equation for bundle friction factor modified by Chen et al. (2013) to make the friction factor trajectory smoother moving through the turbulent boundary now has the exponent λ reassessed to the value of 7.
3. The UCTD is now applicable to 7-pin bundle geometry. This has been achieved by adjusting the bundle average friction factor predicted by CTD for most bundle geometries such that the bundle fiction factor increases as the pin number increases. The cause of the previous inverse behavior was identified as the formulation of the wire drag and wire swirl empirical constants. A new process for finding these empirical constants is proposed and the constants set is calibrated by an 80 bundle data set. For Rehme's set of twenty 7 pin bundle experiments, the mean error prediction is now 9% which is about the measurement uncertainty and improved from 26% with CTD.

The new correlation incorporating the above three improvements to the original CTD correlation is designated as the Upgraded CTD (UCTD) correlation. For the available 118 wire-wrapped bundles with pin number greater than 7 bundles, UCTD predicts the data in the transition and turbulent regimes with a mean error of 0.95% and a 90% confidence interval of ± 14.8%, while both the CTD and the Rehme correlations (REH) have 1.5% higher values of this index. For the 27 available bundles with laminar data,(none of which are as small as 7 pin bundles) the performance of UCTD is slightly better than CTD with mean and RMS values of −2.0%, and 9.5% versus −3.0%, and 9.6%. (The REH correlation is not applicable to the laminar regime).

A web-based numerical code of the UCTD correlation which incorporates these advances has been provided on the web for convenient design and research use.

1. Introduction

1.1. Purpose of this paper

The purpose of the paper is to provide enhancements for both design and research application of the existing Cheng and Todreas (CT) correlation. The experimental confirmation of these correlation enhancements has been made possible by the sixteen additional wire -wrapped rod bundle experiments reported since the publication of our original bundle pressure drop correlation which are summarized in Section 1.3 Literature review below. For design application the correlation updates include redefinition of the laminar to transition

* Corresponding author at: 101, Section 2, Kuang-Fu Road, LTM Building Room 111, Hsinchu 30013, Taiwan.
E-mail address: shihkueichen@gapp.nthu.edu.tw (S.K. Chen).
[1] Formally legally known as S.K. Cheng.

https://doi.org/10.1016/j.nucengdes.2018.05.010
Received 14 February 2018; Received in revised form 3 May 2018; Accepted 7 May 2018
0029-5493/

Nomenclature

A	Axial average flow area
A_r	Projected area of wire in a subchannel
C_f	Friction factor constant defined in Eqs. (A1) and (A2)
D	Rod diameter
De	Equivalent hydraulic diameter
D_w	Wire diameter
f	Darcy friction factor, if no subscript means bundle average value
H	Wire lead length
L	Axial Length
N	Number of each kind of subchannel in the bundle
Nr	Number of pins in the bundle
P	Rod pitch
ΔP	Pressure drop
P_w	Wetted perimeter
Re	Reynolds number ($=\rho VDe/\mu$), if no subscript means bundle average value
Re_{bL}	Laminar to transition boundary Reynolds number
Re_{bT}	Transition to turbulent boundary Reynolds number
V	Axial velocity
W	Edge pitch parameter defined as (D + gap between rod and bundle wall)
W_d	Wire drag constant
W_s	Wire swirl constant
X	Flow split parameter for each subchannel defined as (V_i/V_b)
ρ	Coolant density
μ	Dynamic viscosity
θ	Angle which the wire makes with respect to vertical axis
Ψ	Intermittency factor
m	Mean value of the normal distribution
σ	Standard deviation of the normal distribution
λ	Exponent used in revised transition friction factor formulae

Subscript

i	1, 2, 3 or b denote interior, edge, corner subchannel type, or bundle average, respectively
f	Denotes friction
L	Denotes laminar flow region
T	Denotes turbulent flow region
tr	Denotes transition flow region

Superscript

‘	Denotes equivalent bare rod values (without considering wire)

boundary, updated formulae for the friction factor in the transition regime and reformulation of fitted constants for wire drag (W_d) and wire swirl (W_s) to more correctly predict the effect of bundle pin number variation. For research application the applicable range of the CTD correlation is extended to the seven pin bundle geometry. Importantly the trend of friction factor with pin number has been focused upon to yield the correct trend of friction factor increase with increasing number of pins albeit at a decreasing rate. The strategy and structure of the original correlation is summarized next in Section 1.2 to provide the context for the proposed enhancements.

1.2. The existing Cheng and Todreas correlation for wire wrapped bundle pressure drop

The Cheng and Todreas correlation (CT) for hexagonal wire-wrapped rod bundle pressure drop was published in 1986. The correlation was based on the development of friction factors for the three types of hexagonal bundle subchannels; namely, interior, edge and corner subchannels, as illustrated in Fig. 1. The bundle average friction factor is predicted by subchannel friction factors based upon the fact that pressure drops are the same for different subchannel, i.e., neglecting entrance, exits and momentum losses. It has been enhanced by Chen et al. (2013) by modification of the transition region correlation in the immediate vicinity of the transition to turbulent region boundary and validated in 2014 (Chen et al., 2014) as the superior correlation available in the literature for bundle geometries of both design and research interest.

The experimental data of bundle average friction factor are determined by the measured pressure drop over a length L in a wire-wrapped rod bundle.[2] These experimental data clearly show that there are three flow regimes for this parameter. Below a specific bundle Reynolds number the friction factor is proportional to $1/Re_b$, hence, the laminar regime. As the Re_b increases the flow enters the transition regime, and finally at a sufficiently high Reynolds number the flow becomes fully turbulent. These two transition Reynolds numbers Re_{bL} and Re_{bT} are two cornerstones of the CT correlation.

The bundle average friction factor constant, C_{fbT} and C_{fbL} for the turbulent flow regime and the laminar flow regime, respectively, are determined by $C_{fb} = f_b \times Re_b^m$ with m = 0.18 for the turbulent regime and m = 1 for the laminar regime. These bundle average friction factor constants are functions of geometrical parameters and subchannel friction factor constants C_{fiT} or C_{fiL}, which contain the empirical constants W_d and W_s, formulated to reflect the specific effect of the wire wrapping as described below.

The enhancement of the wire-wrapped subchannel friction factors relative to the bare rod values are caused by two hydrodynamic mechanisms. For the interior subchannel, the pressure loss due to wire drag was evaluated by a theoretical drag loss characterized by an empirical constant, W_d (wire drag constant). The other pressure loss enhancing mechanism effect is a swirl flow induced by the wire, creating a tangential flow which increases the flow path in the edge and corner subchannels, hence the pressure loss, and the friction factor for these subchanneis. The empirical constant W_s (swirl flow constant) was used to reflect the actual value of this effect. These two constants are geometrical parameters as well as flow regime dependent, and must be

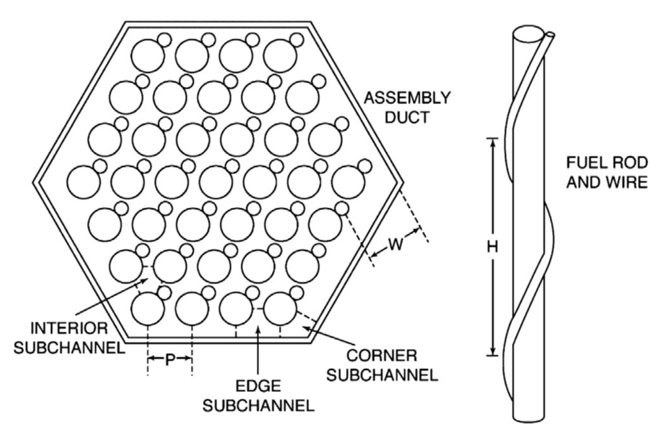

Fig. 1. Typical sodium cooled fast reactor (SFR) wire-wrapped assembly and rod configuration.

[2] Bundle axially average friction factor $f_b = \Delta P(De_b/L)(2/(\rho V_b^2))$. The pressure at each axial plane is that averaged across the bundle cross section.