



Mathematical spacer grid models for single phase flow



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ABSTRACT

The fuel rods in pressurized water reactor (PWR) and boiling water reactor (BWR) cores are supported by spacer grids. Even though spacer grids add to pressure loss in the reactor core, spacer grids have several benefits in light water reactors (LWRs). Some of these benefits are: (i) increasing turbulence at the bottom of the reactor core for better heat transfer in single phase region of LWRs, (ii) improving departure nucleate boiling ratio results for PWRs, and (iii) improving critical power ratio (CPR) values by increasing the thickness of film in annular flow regime in the top section of the reactor core of BWRs. Several mathematical models have been developed for single and two phase pressure loss across the grid spacer. Almost all of them significantly depend on Reynolds Number. Spacer designs have evolved (incorporating mixing vanes, springs, dimples, etc), resulting in complexity of the analysis across the grid. The models have been compared not only theoretically but also quantitatively. For the quantitative comparisons, this work compares results of mathematical spacer models with experimental data of BWR Full Size Fine Mesh Bundle Tests (BFBT). The experimental data of BFBT provides very detailed experimental results for pressure drop by using several different boundary condition and detailed pressure drop measurements. Two bundle types of BFBT, the current 8×8 type and the high burn-up 8×8 type, were simulated. There are two also types of spacers in the BFBT program – ferrule type and grid type. Therefore, the experimental data of BFBT used a wide range of boundary conditions of BWRs. This paper analyzes mathematical models of spacer grids for a portion of available data. It was observed and discussed that pressure drop values due to spacer models can be significantly different for single phase flow.

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1. Introduction

Fuel bundles of both PWR and BWR reactors require spacers to maintain the integrity and spacing of the slender fuel rods. These spacers provide benefits such as increased mixing and turbulence, which increases heat distribution, leading to better Departure from Nucleate Boiling (DNB) conditions in PWRs. The spacer grids also enhance critical power ratios by increasing the thickness of the liquid layer in BWRs. However, spacer grids also cause a pressure loss, which must be engineered into fuel bundle performance and operation.

Flow within a rod bundle involves a number of complicated factors, such as cross flow, (de)entrainment of liquid layer, bubble or droplet break up/join. This requires specialized 3 dimensional computational fluid dynamics (CFD) for complete flow characterization, however, commercially developed CFD models are proprietary and require extensive programming and cost to implement. In the public domain, a number of one dimensional models have been developed that can benefit in initial design and decision making,

if the models demonstrate both accuracy and precision where applied.

Japan's Nuclear Power Engineering Corporation's (NUPEC) BFBT data was used for the OECD/US-NRC BFBT Benchmark data based on extensive BWR boundary conditions. BFBT data includes detailed measurements for pressure loss, void fractions and temperatures throughout BWR bundles. The objective of the BFBT Benchmark is to create a framework to validate codes and models with detailed measurements.

This study consists of compiling and comparing available and established single phase equations and models, to both each other and BFBT experimental data, to determine how conditions used to develop the models apply to other conditions. This study also attempts to identify which flow characteristics have definable effects on the available spacer grid pressure loss models. Then these models could identify more extensive modeling, and assist in choosing programming and training.

The focus of this study is to describe the available mathematical models of spacer grids, and validate them with experimental results for single phase flow through a spacer grid, over a range of pressures and flows, to identify if they are precise and accurate, with updated measurements, over a variety of conditions. This

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Nomenclature

ΔP_{in-out}	pressure change between two points (Pascal) (kg/m-s ²)	$C_{V(D)}$	Schikorr/Bubelis drag coefficient
$\Delta P_{inertia}$	pressure to start movement	D_h	general hydraulic diameter (m)
$\Delta P_{acceleration}$	pressure change from compression	$D_{H\ B}$	hydraulic diameter of the bundle (m)
ΔP_{form}	pressure change from channel obstruction	$D_{H\ SP}$	hydraulic diameter of the spacer (m)
$\Delta P_{gravity}$	pressure change from elevation change	g	gravity (9.81 m/s ²)
$\Delta P_{friction}$	pressure change from channel friction	G_B	mass flowrate through the fuel bundle open area (flux) (kg/s – m ²)
ΔP_x	general pressure loss correlation, x is a place holder	G_{SP}	mass flux through the spacer – (kg/s – m ²)
$\Delta P_{(CO)}$	Chun/Oh pressure loss correlation	h	elevation change (m)
$\Delta P_{(DS)}$	DeStourder pressure loss correlation	H_{SP}	height of a spacer (m)
$\Delta P_{(I)}$	Idelchik pressure loss correlation	K_x	general pressure loss coefficient
$\Delta P_{(IN)}$	In pressure loss correlation	$K_{(B,IN)}$	In combined fuel bundle pressure loss coefficient
$\Delta P_{(RT)}$	Rehme/Trippe pressure loss correlation	K_c	Tong/Weisman contraction pressure loss coefficient
$\Delta P_{(S)}$	Spengos pressure loss correlation	$K_{(CO)}$	Chun/Oh pressure loss coefficient
$\Delta P_{(SB)}$	Schikorr/Bubelis pressure loss correlation	K_e	Tong/Weisman expansion pressure loss coefficient
$\Delta P_{(TW)}$	Tong/Weisman pressure loss correlation	K_f	Shiralkar friction pressure loss coefficient
$\Delta P_{(V)}$	Rehme pressure loss correlation	$K_{fric,grid}$	Chun/Oh grid frictional pressure loss coefficient
Θ	area modifier for the spacer flow	$K_{fric,rod}$	Chun/Oh rod frictional pressure loss coefficient
ϵ	blockage ratio – grid area/bundle flow through area	$K_{form,grid}$	Chun/Oh spacer form pressure loss coefficient
ε	rod roughness	$K_{form,mixing}$	Chun/Oh mixing vane form pressure loss coefficient
σ	contraction ratio – spacer flow through area/bundle flow through area	$K_{(Idelchik)} = K_{(I)}$	Idelchik pressure loss coefficient
f_{turb}	Shiralkar turbulent friction coefficient	$K_{(RT)} = \xi$	Rehme/Trippe pressure loss coefficient
f	general friction coefficient	$K_{(SH)}$	Shiralkar pressure loss coefficient
$f_{(D)}$	friction coefficient for the Chun/Oh and In correlations	$K_{(V)}$	Rehme pressure loss coefficient
ρ	density (kg/m ³)	L	length (m)
A_B	flow through area of the channel (Bundle) (m ²)	L_{turb}	length to turbulent transition (m)
A_{rod}	cross sectional area of fuel and water rods (m ²)	PWR	pressurized water reactor
A_{SP}	frontal area of spacer (m ²)	Re_B	Reynolds Number (bundle)
BWR	boiling water reactor	Re_L	Reynolds Number (length of flat surface)
C_x	general drag coefficient	Re_{SP}	Reynolds Number (spacer)
$C_{d,0\ IN}$	In form drag coefficient	Perimeter of Channel	the outside walls of the channel (m)
$C_{d,i}$	Chun/Oh form drag coefficient	Perimeter of Rods	the circumference of the fuel and water rods (m)
$C_{d,grid}^{fric}$	In grid frictional drag coefficient	U	general velocity (m/s)
$C_{d,lam}^{fric}$	In laminar flow frictional drag coefficient	WA_{rod}	is the wetted area of the rods along the height of the spacer (m ²)
$C_{d,rod}^{fric}$	In rod frictional drag coefficient	WP_B	wetted perimeter bundle, walls of the channel plus the perimeter of the rods (m)
C_{DS}	DeStourder drag coefficient	WP_{SP}	wetted Perimeter Spacer length of spacer components that contact the flow (m)
$C_{f,lam}^{fric}$	Chun/Oh laminar flow frictional drag coefficient		
$C_{f,turb}^{fric}$	Chun/Oh turbulent flow frictional drag coefficient		
C_S	Spengos drag coefficient		
C_{SH}	Shiralkar drag coefficient		
C_V	Rehme drag coefficient		

study indicates there is no universal equation that fits all boundary conditions accurately. However, by using the BFBT experimental data, this study identifies boundary conditions for which a 1 dimensional spacer grid model can be useful.

2. Methods

2.1. Spacer grid pressure drop equation

To define the specific spacer grid pressure loss term, and discuss the mathematical terms for the spacer grid, this section presents a brief overview of all pressure loss terms, including two phase flow. The total two phase flow pressure loss consists of the terms shown in Eq. (1) (Todreas and Kazimi, 2012):

$$\Delta P_{out-in} = \Delta P_{inertia} + \Delta P_{acceleration} + \Delta P_{form} + \Delta P_{gravity} + \Delta P_{friction} \quad (1)$$

where ΔP_{out-in} is the change in pressure from the inlet to the outlet; $\Delta P_{inertia}$ is the pressure change from the added force initiating flow; $\Delta P_{acceleration}$ is the pressure change from compression in gas phase

flows; ΔP_{form} is the pressure loss from a geometric change in the channel, which in this study will be the spacer; $\Delta P_{gravity}$ is the pressure loss from the force necessary for vertical movement and $\Delta P_{friction}$ is the pressure loss from friction in the channel.

This study uses single incompressible phase, steady state flow, measured at the same size cross section before and after the BFBT database spacer. The incompressibility is based on the conditions of the experiment, which uses liquid water, at constant pressure, for each set of tests. The flow conditions negate the acceleration, $\Delta P_{acceleration}$, and inertia, $\Delta P_{inertia}$, terms. The first general pressure loss factored into the test results, to isolate the spacer pressure loss, is pressure loss from elevation rise, calculated by Eq. (2) (Todreas and Kazimi, 2012):

$$\Delta P_{gravity} = \rho gh \quad (2)$$

where ρ is the density of the coolant, g is acceleration due to gravity and h is the vertical distance the coolant rises.

The second general pressure loss, factored into the test results, is the frictional pressure drop along the channel before and after the spacer, calculated by Eq. (3) (Todreas and Kazimi, 2012):

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