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Experimental studies for hydraulic characteristics of corrugated channel for printed circuit steam generator (PCSG)

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1. Introduction

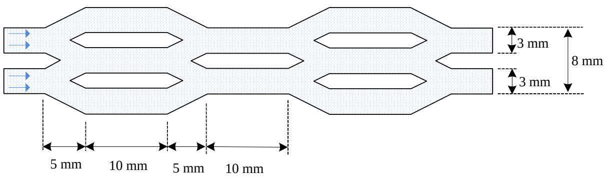
When researchers and engineers design energy production systems, system miniaturization and enhancing energy production efficiency are crucial challenges. This is also an important issue in the development of small modular reactor (SMR), which aim to replace conventional large-scale nuclear reactors. Currently, SMR adopt shell & tube steam generators. However, to improve efficiency, the heat transfer rate must be increased, which requires longer steam generators. Therefore, the development of steam generators that can increase heat transfer rates while being smaller in size is essential for SMR miniaturization. Research on printed circuit steam generator (PCSG) is studied actively to replace traditional steam generator.

PCSG is formed by chemically etching channels onto a plate, and the plate with channels is then stacked and bonded using a diffusion bonding process to form a compact and highly efficient steam generator, unlike traditional heat exchangers known for their high efficiency despite their small volume [1]. One of the main issues in recent PCSG research is the thermal-hydraulic performance depending on the design of the internal channels. Various models of internal channels, such as zigzag types [2,3], airfoil types [4,5], and S-shaped type [6], have been studied through simulations and experiments. Among them, tangled type (in this paper, corrugated channel) was studied by Sung et al. [7]. However, analysis of this corrugated channel studies has only been conducted between 1000 and 3000 Reynolds number. The results in laminar flow also was not measured.

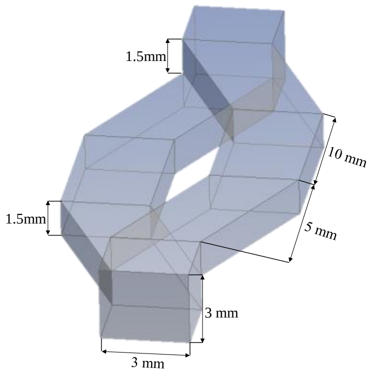
In this study, before investigating the heat transfer performance of the tangled type, hydrodynamic characteristic of the designed channels will be studied in laminar flow, turbulent flow.

2. Methodology

2.1. Test section design



(a)



(b)

(c)

Fig. 1. (a) dimension, (b) Individual unit component, and (c) picture of corrugated channel.

The size of the corrugated channel investigated in this study is Fig. 1. Patterns were printed on two stainless steel plates and welded to make corrugated channel. Fig. 1(a) represents a dimension of corrugated channel, Fig. 1(b) is a single unit corrugated channel, and Fig. 1(c) is picture of one side of plates. The channel exhibits a corrugated shape with sections of 5mm, 10mm, 5mm, and 10mm repeating. Additionally, the initial height is 10mm at the 3mm point, while the remaining sections repeat a pattern structure with a height of 1.5mm.

2.2 hydraulic parameters

The friction factor was calculated based on the following equation, which relates pressure drop to velocity:

$$f = \frac{2\Delta P D_h}{\rho v^2 L} \tag{1}$$

The Reynolds number (Re) was calculated based on the hydraulic diameter as follows:

$$Re = \frac{\rho v D_h}{\mu} \tag{2}$$

In this case, the hydraulic diameter (D_h) and velocity (v) used in equations (1) and (2) were calculated by the following expressions (3) and (4):

$$D_h = \frac{4V}{A_{wet}} \tag{3}$$

$$v = \frac{\dot{Q}}{A_c} \cdot \frac{1}{N} \tag{4}$$

2.3 Experiments apparatus

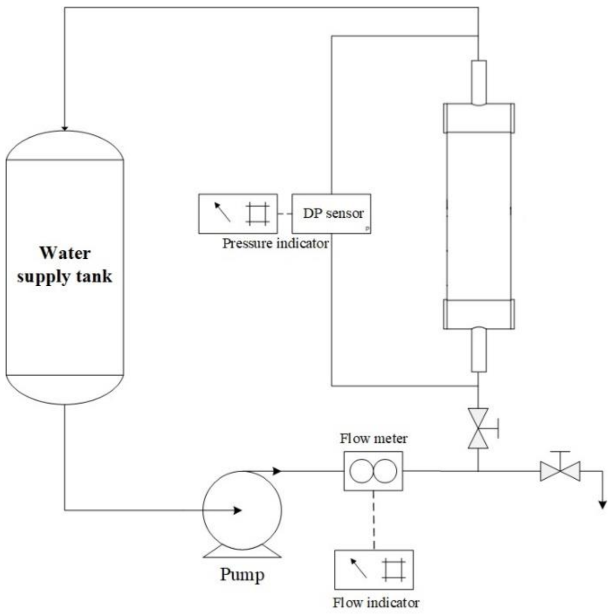


Fig. 2. Schematic of the experimental setup

Fig. 2 depicts a schematic diagram of the experimental setup design. To conduct experiments within the Reynolds number range of 1000 to 20000 as calculated by equation (2), pumps ranging from 0L/min to 10L/min were utilized.

Flow measurements were conducted using KYONGIN's KIF series turbine flowmeter. The KIF510 model was employed for flow rates from 0L/min to 2L/min, while the KIF540 model was used for flow rates from 2L/min to 10L/min. The error range of each flowmeter at full scale is ±3%.

Differential pressure gauges from Sensys's DWS series were used. It installed between inlet and outlet of channel. For flow rates below 2L/min, differential pressure gauges within the range of 0kPa to 10kPa were utilized for more precise measurements, whereas for flow rates equal to or above 2L/min, differential pressure gauges within the range of 0kPa to 50kPa were employed. The measurement error at full scale for the differential pressure gauges used is 0.25%.

3. Result and Discussion

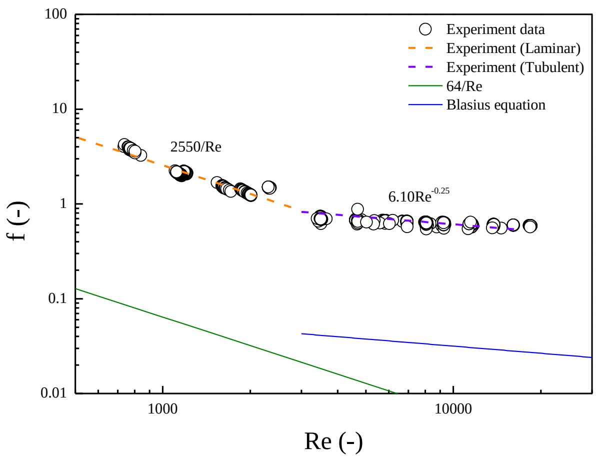


Fig. 3. Dimensionless analysis for hydraulic performance using Reynolds number and friction factor.

In Fig. 3, experimental results and correlation equations are presented to distinguish laminar flow and turbulent flow in the Reynolds number range of 1000 to 20000. When Reynolds numbers below 3000, slope of experiment result is similar to correlation equation 64/Re. Thus, correlation of experiment can be expressed by equation (5):

$$f = 2550/Re \tag{5}$$

This is 39.84 times larger than the magnitude of the 64/Re. Also Reynolds number is above 3000, experimental results indicated turbulent flow. By comparing Blasius equation, results have the similar slope. the correlation can be expressed by equation (6):

$$f = 6.10Re^{-0.25} \tag{6}$$

This is 19.30 times larger than the magnitude of Blasius equation ($f = 0.316Re^{-0.25}$). This could be interpreted that corrugated channel could affect the pressure loss due to the vortex or intermixing phenomenon in the corrugated channel. Besides that, inlet and outlet headers configuration also give effect on the friction factor. However, the effect of the header shape and configuration will be considered in the further study.

Furthermore, the transition zone was observed at a Reynolds number near 3000. This range is not significantly different from the Reynolds number range of 2100 to 4000 which could observe at the transition point of a standard circular pipe. Therefore, validation by using simulation is necessary for this part.

4. Conclusions and further study

Experiment with corrugated was conducted to investigate the hydrodynamic characteristics of the corrugated PCSG. The experiments measured the friction factor according to the Reynolds number, ranging from 1000 to 20000 to search laminar flow and turbulent flow. The results show a change in slope around Reynolds number 3000. At Re<3000, a slope is similar with 64/Re. While at Re>3000, a slope like the Blasius equation was observed. Also, magnitude of experiment result is larger than correlation. It means PCSG made by corrugated channel can affect pressure drop by comparing shell & tube steam generators. Furthermore, a transition zone was observed around the Reynolds number of 3000.

This study is excluding the effect of header shape and configuration. Further, this will be considered as another main parameter for better understanding the hydrodynamic characteristics of the proposed corrugated design.

Nomenclature

A_c	Channel Area	$[m^2]$
A_{wet}	Wetted area	$[m^2]$
D_h	Hydraulic diameter	$[m]$
L	Length of channel	$[m]$
N	Number of the entrance of channel	
ΔP	Differential pressure	$[Pa]$
$\dot{Q}$	Flow rate	$[m^3 \cdot s^{-1}]$
ρ	Density	$[kg \cdot m^{-3}]$
μ	Dynamic viscosity	$[kg \cdot m^{-1} \cdot s^{-1}]$
v	Velocity	$[m \cdot s^{-1}]$
f	Friction factor	$[-]$
Re	Reynolds number	$[-]$

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