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Effect of Wire Pitch on Capacity of Single Staggered Wire and Tube Heat Exchanger Using Computational Fluid Dynamic Simulation

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ABSTRACT

Single staggered is a design development of normal wire and tube heat exchanger that wires are welded with staggered configuration on two sides. Capacity of wire and tube heat exchanger is the ability of the heat exchanger to release heat. The objective of this study is to analyse the effect of wire pitch (p_w) on capacity of single staggered wire and tube heat exchanger. The research method uses Computational Fluid Dynamic (CFD) simulation by ANSYS Fluent to analyse heat transfer of wire and tube; also to analyse airflow at surface the wire and tube. The simulation is experimentally validated by measuring temperatures at some points of wire and tube. Based on results, temperature contours increasing capacity of heat exchanger depend on smaller wire pitch that the highest value is 72.02 W at p_w 7 mm. The reason is smaller wire pitch increases area of convection heat transfer surface. Whereas, airflow patterns show air move slowly at the wire and tube surface and flow with free convection. This study contributes new design of wire and tube heat exchanger with CFD and it can be applied to improve the performance of this heat exchanger in refrigeration system and other applications.

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NOMENCLATURE

cp	Specific heat (J/kgK)	T_s	Surface temperature (K)
d_t	Tube diameter (m)	T_∞	Ambient air temperature (K)
d_w	Wire diameter (m)	**Greek Symbols**	
g	Gravity (m/s^2)	β	Expansion coefficient of air (1/K)
H	Wire and tube height (m)	ε	Thermal emissivity
h_c	Coefficient convection (W/m^{2}K)	μ	Dynamic viscosity (Ns/m^2)
h_o	Coefficient overall (W/m^{2}K)	ρ	Density (kg/m^3)
h_r	Coefficient radiation (W/m^{2}K)	Φ	Wire and tube specific ratio
k	Thermal conductivity of air (W/mK)	σ	Stefan-boltzmann constant 5.67 x 10-8 W/m^{2}K^4
$\dot{m}$	Massflow rate (kg/s)	**Subscripts**	
Nu	Nusselt number	c	Convection
p_t	Tube pitch (m)	in	Inlet tube
p_w	Wire pitch (mm)	o	Overall
q	Heat rate (W)	out	Outlet tube
Ra	Rayleigh number	r	Radiation
S_t	Tube specific ratio	s	Surface of wire and tube
S_w	Wire specific ratio	t	Tube
T_{in}	Inlet temperature (K)	w	Wire
T_{out}	Outlet temperature (K)	∞	Ambient air

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1. INTRODUCTION

Wire and tube heat exchanger is commonly used as component of refrigeration system in industry or life. Wire and tube consists of a concentric tube with wires welded on two sides of the tube. Wires as a fin in this wire and tube were welded in the inline arrangement and facing each others. Wires are used to increase total area of convention heat transfer. The more area contact in a heat exchanger will increase value of heat transfer [1]. This is applied by Topcuoglu [2] that used coiled tube for increasing heat transfer. Zhang et al. [3] studied condenser in gas engine-driven heat pump for heating and cooling application.

Many development designs are investigated to improve performance wire and tube heat exchanger with inline arrangement wire. For examples, reasearch was to develop wire and tube model with mathematical approach using finite element methods [4-6].

Research by Arsana et al. [7] showed a new design of wire and tube with single staggered arrangement of wires has better heat transfer rate. This research used three variations of wire pitch (7 mm, 14 mm, and 21 mm) and developed numerical modelling to optimize design. It still needs further investigation, especially to concern effect of small wire pitch on heat transfer. At the small wire pitch, the capacity will be optimal but it is still more investigation to find out optimal design precisely.

Nowadays, researches often use CFD simulation to investigate in heat transfer. Such as Arsana et al. [8] investigated natural convection heat transfer from single staggered wire and tube comparing with normal direction. Gonul et al. [9] investigated air side force convection on several variation of wire and tube. Sengupta et al. [10] investigated combustion gases of stove system for cooking. Teja et al. [11] analysed surface temperature on water harvesting.

Based on thoughts above, single staggered arrangement of wires still needs further investigation about the effect of wire pitch on heat transfer of this heat exchanger in free convection conditions. So, present study investigates effect of wire pitch with three variations (7 mm, 9 mm, and 11 mm) on capacity of single staggered design.

2. MATERIALS AND METHODS

2. 1. Materials Steel is used as material of wire and tube and oil thermo-32 is used as hot working fluid which flows inside tube. This study used three inlet variations to figure out the effect of wire pitch at low to high temperature [8]. Beside this, detailed objects as shown in Table 1.

TABLE 1. Detailed specification of some single staggered wire and tubes

Property	Value or Information
Wire and tube material	Steel
Heat exchanger height	0.445 m
Heat exchanger width	0.431 m
Tube out diameter	0.0048 m
Tube in diameter	0.0032 m
Property	**Value or Information**
Wire diameter	0.0012 m
Wire pitch	7, 9, 11 mm
Total concentric tube	12
Number of wires in p_w 7 mm	62
Number of wires in p_w 9 mm	48
Number of wires in p_w 11 mm	40
Tube pitch	0.4 m
Fluid	Thermo oil-32
Mass flow rate	0.0012 kg/s
Inlet temperature	313 K, 333 K, and 353 K
Specific heat (Cp)	2000 J/kg K
Density (ρ)	856 kg/m^3

2. 2. Simulation Setup This research was conducted by developing models using CFD simulations by ANSYS Fluent with experimental validation. first step, a simulation model at p_w 7 mm was validated by using experiment. Then, the data is used as a reference for other simulations.

There were three steps to simulate model was pre-processing, processing, and post-processing [12]. In the initial stage of conducting CFD simulation was created 3D geometry model. There were two types of geometry models. Wire and tube geometry models were used for flow simulation inside tubes and air geometry models were used for airflow simulation at wire and tube surface. The mesh method chosen for the wire and tube models were unstructured mesh with hexahedral mesh [13]. While the mesh method chosen for the wire and tube air models were unstructured mesh with tetrahedral mesh [13].

After meshing, next step determines physical-mathematical modeling, material, operating conditions, boundary conditions, and completion techniques. First, determining general conditions, where conditions generally used pressure-based by including the influence of gravity in solving and steady-state conditions [11]. Second, choosing the physical equations used for this simulation were the energy equation, and the viscous model k-epsilon for wire and tube geometry models [14] and k-omega STT for air at surface wire and tube geometry models [15].

2. 3. Experimental and Validation Method

Simulations were validated by the experiment. Data validation used only at wire and tube p_w 7 mm and inlet temperature at 313 K. Validation was conducted by measuring inlet, outlet and nine temperatures of the wire and tube [7-8]. The data of p_w 7 mm was compared to simulations result with maximum error limit of ± 5% [7-8]. Furthermore, when the data had been valid, the data applied as reference to simulated at pw 9 mm and pw 11 mm; installation experiment are shown in Figure 1

2. 4. Data Analysis

Capacity of a heat exchanger [5] can be related as follows:

$$q = \dot{m}\, c_p\, (T_{in} - T_{out}) \tag{1}$$

Wire and tube heat exchanger naturally releases heat to ambient air. According to Bansal and Chin [5] free convection is overall convection coefficient consisting radiation and convection coefficients. The equations are shown below:

$$h_o = h_c + h_r \tag{2}$$

$$h_r = \varepsilon.\sigma.(T_s^4 - T_\infty^4)/(T_s - T_\infty) \tag{3}$$

$$\text{Nusselt Number (Nu)} = \frac{h_c\,.\,H}{k} \tag{4}$$

Empirical equation for Nusselt Number [5] is shown below:

$$Nu = 0.66\,\left(\frac{Ra\,.\,H}{dt}\right)^{0.25}\{1 - [1 - 0.45\,\left(\frac{Ra\,.\,H}{H}\right)^{0.25}]\,\mathrm{Exp}(-\frac{Sw}{\varphi}) \tag{5}$$

$$R_a = \left(\frac{\beta\rho^2 cp}{\mu\, k}\right).\; g\,(T_s - T_\infty).H^3 \tag{6}$$

$$\phi = \left(\frac{28{,}2}{H}\right)^{0.4}.\,S_w^{0.9}\,.\,S_t^{-1} + \left(\frac{28{,}2}{H}\right)^{0.8}.\left[\frac{264}{Ts - T\infty}\right]^{0.5}.S_w^{-1.5}.\,S_t^{-0.5} \tag{7}$$

$$S_w = (p_w - d_w)/d_w,\ \text{dan}\ S_t = (p_t - d_t)/d_t \tag{8}$$

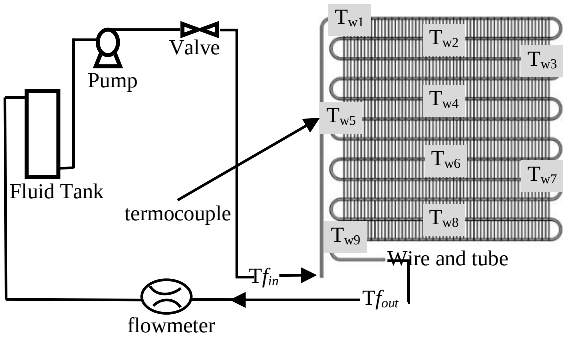


Figure 1. Experiment set up for validation

Basedon above equations, capacity of wire and tube can be found by determining heat transfer inside wire and tube (1) and overall convection coefficient in outside wire and tube heat exchanger (2).

3. RESULT AND DISCUSSION

3. 1. Grid Independence

In simulation process, grid independence used for simulation models is the smallest error [5]. There are three meshes to figure it out at pw 7 mm. The results are shown in Figures 2 and 3.

Based on Figures 2 and 3, the chosen wire and tube mesh is mesh 3 because the mesh 3 produces an average error of 1.32% which is smaller than the others. Meanwhile, the smallest average error of air model at wire and tube is mesh 1 with 3.97%.

3. 2. Simulation Result

Figure 4(a) (b) and (c) show almost the same outlet temperature around 305 K which means three wire and tubes have almost the same heat transfer. However, p_w 7 has better heat transfer because it reaches 305 K faster than the others. It is indicated by reaching 305 K at third row than p_w 9 and p_w 11 reached at fourth and fifth rows. Wire and tube at 313 K inlet just obtains little heat transfer because of small temperature difference between inlet and ambient air [8].

Figure 4(d) (e) and (f) show wire and tubes at 333 K inlet work more optimal than inlet at 313 K. That can be

Figure 2. Grid independence of wire and tube heat exchanger models.

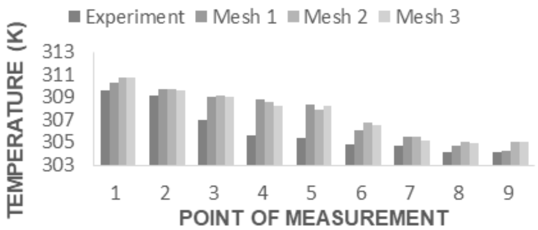


Figure 3. Grid independence of air models at surface wire and tube heat exchanger.

seen from the change in inlet to outlet. P_w 7 mm has the highest heat transfer with temperature difference from 333 K to 307 K. Whereas, p_w 9 mm reaches temperature difference from 333 K to 309 K and p_w 11 mm reaches from 333 K to 311 K.

Figure 4(g) (h) and (i) have highest capacity of heat transfer because they produce significant temperature difference from inlet to outlet is from 353 K to 323 K. These data show the higher inlet temperature will increase heat transfer of wire and tube. The highest temperature difference in order is p_w 7 with 353 K to 323 K, p_w 9 mm with 353 K to 326 K and p_w 11 mm with 353 K to 328 K. These results indicate the smaller wire pitch will increase heat transfer because it has more contact area of heat transfer [5]. These results are supported by Arsana's research [7-8] showed temperature of wire and tube at p_w 7 with 333 K has difference temperature around 26 K from inlet to outlet. However, this simulation is more complete than reported data.

Figure 5 shows the air velocity distribution viewed from the side of wire and tube is very small. That is because the heat transfer of wire and tube occurs from the surface object to ambient air without any external force. The airflow of wire and tube moves due to the temperature difference in each tube row from top part to the bottom part. That causes the air is spread.

The highest velocity occurs at p_w 11 mm as the largest wire pitch has small resistance [8]. Besides, highest velocity occurs at middle tube because there was smallest resistance to flow freely. According to previous research [6] [7] and [10] this is because of the air move following the change in heat of each row on the wire and tube. Air is exposed to heat and expands then from that expansion the air became lighter and raised to the top.

Figure 6 shows correlation between each wire and tube and heat transfer rate. The largest heat transfer is 72.07 W at pw 7 mm with 353 K inlet, and the smallest heat transfer rate is 16.06 W at pw 11 mm with 313 K inlet. It shows smaller wire pitch increasing heat transfer due to more heat transfer area. Figure 6 also shows at the 313 K inlet, heat transfer at the three wire and tubes are not much different. That concludes

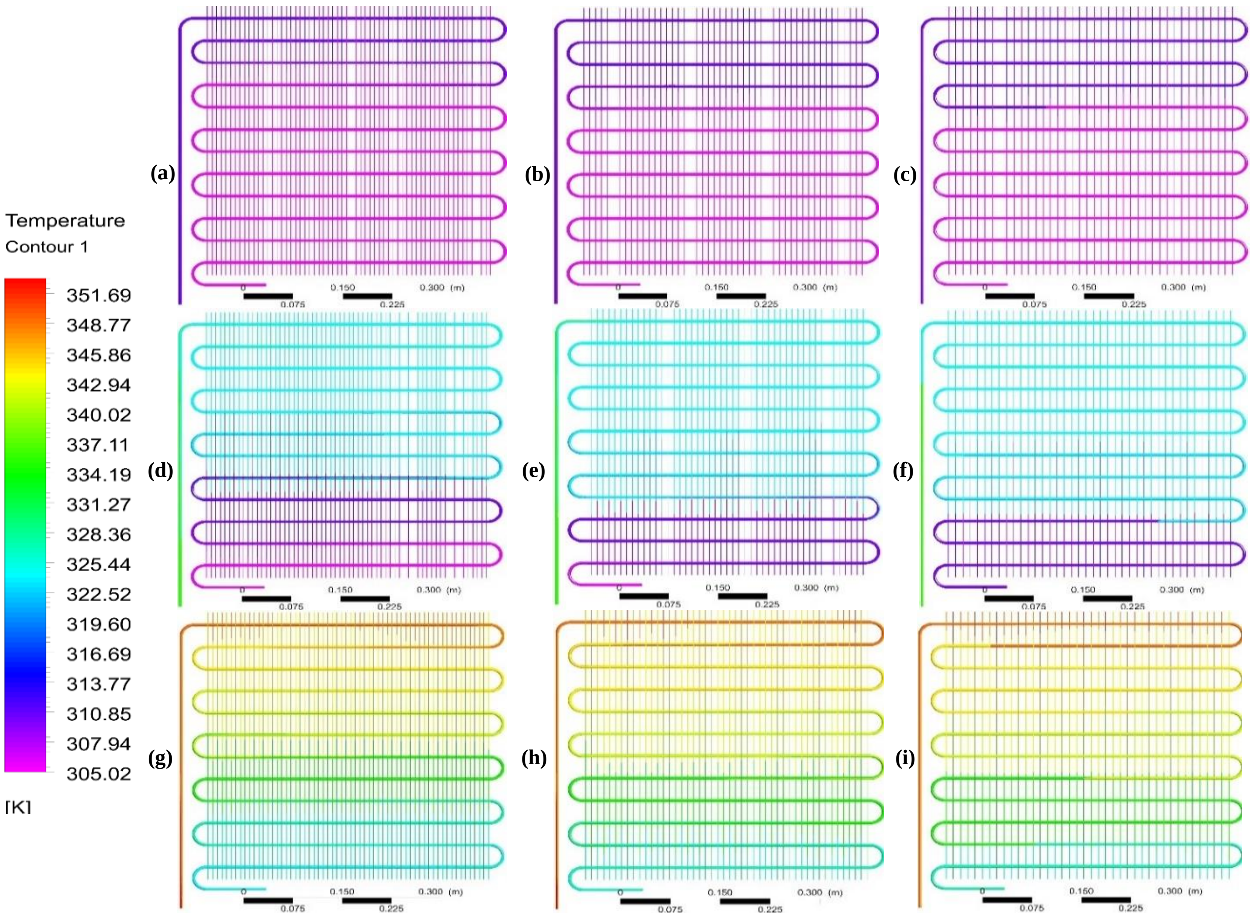
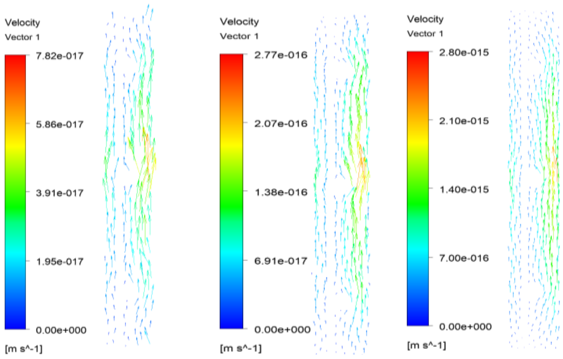


Figure 4. Temperature contours of: **(a)** p_w 7 mm at 313 K inlet. **(b)** p_w 9 mm at 313 K inlet. **(c)** p_w 11 mm at 313 K inlet. **(d)** p_w 7 mm at 333 K inlet. **(e)** p_w 9 mm at 333 K inlet. **(f)** p_w 11 mm at 333 K inlet. **(g)** p_w 7 mm at 353 K inlet. **(h)** p_w 9 mm at 353 K inlet. **(i)** p_w 11 mm at 353 K inlet



(a) (b) (c)

Figure 5. Air current speed vector at wire and tube heat exchangers of inlet 313 K. **(a)** p_w 7 mm. **(b)** p_w 9 mm. **(c)** p_w 11 mm

the low inlet temperature does not require a lot of wires.

This is in line with Arsana's research [7] stated that increasing the number of wires would increase the rate of heat transfer by using inline wire and tube at p_w 7, 14, and 21 mm with 333 K inlet which results in the best rate at p_w 7 mm.

Figure 7 shows the largest coefficient at p_w 7 mm with 353 K inlet is 13.27 W/m^{2}K. While the smallest value at p_w 11 mm with 313 K inlet is 8.68 W/m^{2}K. Figure 9 shows convection coefficient increasing because of smaller wire pitch and the larger inlet temperature. Meanwhile, the radiation coefficient will produce almost the same value because the average temperature of all wire and tubes is not too large so that it emits little radiation. These results are supported by previous studies such as Bansal and Chin [5], Arsana et al. [7] which obtained the best capacity value was proportional to the area of heat transfer.

Correlation between heat transfer and overall convection coefficient is interconnected with each other. Heat transfer rate is proportional with overall heat transfer coefficient because high heat transfer rate increases air thermal conductivity. This is in line with previous study by Barzegar and Fallahiyekta [16] stated that increasing heat transfer depends on increasing fluid thermal conductivity and decreases boundary layer thickness.

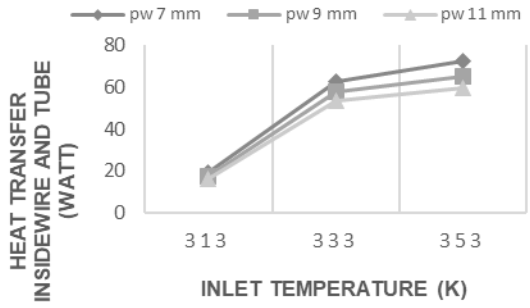


Figure 6. Heat transfer at each inlet temperature and each wire pitch

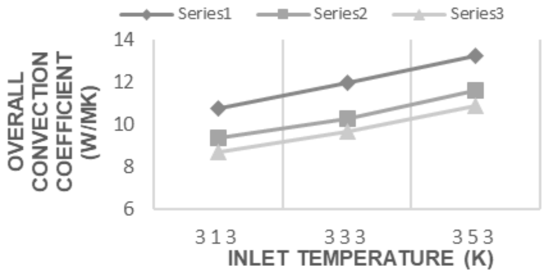


Figure 7. Air convection coefficient at each wire and tube.

4. CONCLUSION

Based on the research that the smaller wire pitch makes greater heat exchanger capacity at each inlet temperature. But, Wire and tube with small wire pitch does not work optimally at low temperature because the small wire pitch causes the heat transfer working only on top part instead bottom part of wire and tube heat exchanger.

Air simulation shows current convection flowing from the bottom to the top at wire and tube surface it is because the air became lighter when it is exposed by heat from inside tube. The simulation result can help understand heat transfer phenomenon to occur outside surface of single staggered wire and tube heat exchanger. These results can be used as a reference for using optimal wire and tube heat exchanger. If it is used at low temperature, it is recommenced to use wire and tube with large wire pitch

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Persian Abstract

چکیده

توسعه طراحی مبدل حرارتی تیغه دار معمولی و لوله ای است که انحناع از دو طرف با پیکربندی مبهم جوش داده می شوند. ظرفیت مبدل حرارتی تیغه دار و لوله ، توانایی مبدل حرارتی در انتشار گرما را دارند. هدف از این مطالعه ، بررسی تأثیر ضخامت موانع تیغه دار بر ظرفیت حرارتی یک مبدل حرارتی لوله منفرد است. روش تحقیق از شبیه سازی دینامیکی سیالات محاسباتی (CFD)بکمک نرم افزار ANSYS Fluent برای تجزیه و تحلیل انتقال حرارت مبدل تیغه دار و لوله استفاده می کند. همچنین برای تحلیل جریان هوا در سطح تیغه و لوله. این شبیه سازی به صورت آزمایشی با اندازه گیری دما در برخی از نقاط تیغه و لوله تأیید می شود. بر اساس نتایج ، کانتورهای دما که ظرفیت مبدل حرارتی را افزایش می دهد ، به تیغه کوچکتر بستگی دارد که بیشترین مقدار آن ۷۲.۰۲ W در pw 7 میلی متر است. دلیل این است که خمش تیغه کوچکتر باعث افزایش سطح انتقال حرارت همسو می گردد. در حالی که ، الگوهای جریان هوا نشان می دهد هوا به آرامی در سطح تیغه و لوله حرکت می کند و با انتقال حرارت بطور آزاد جریان می یابد. این مطالعه به طراحی جدید مبدل حرارتی تیغه و لوله با استفاده از CFD کمک می کند و می تواند برای بهبود عملکرد این نوع مبدل حرارتی در سیستم تبرید و سایر کاربردها کاربرد داشته باشد.