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Correlation of Steam Velocity and Pipe Diameter with Heat Transfer Performance on 120° Half-Pipe Jacket

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ABSTRACT

Double jacket mixing tanks offer temperature control and versatility for industrial processes where temperature-sensitive materials need to be mixed, stored, or processed. The selection of the appropriate jacket type in a double-jacket mixing tank is based on the structural strength and the optimal heat transfer performance. The type of jackets can be conventional, dimple, and half-pipe. The conventional jacket is easier to manufacture, but it is not resistant to high temperature and pressure. The dimple jacket has good heat transfer, but it is susceptible to damage. The half-pipe jacket has good structural strength, but its heat transfer is affected by the central angle and pipe diameter. 120° central angle has greater heat transfer and pressure drop than 180° central angle. In order to determine the effects of steam velocity on heat transfer performance, heating time, and pressure drop of the 120° half-pipe jacket, research occurred on pipes with 2, 2.5, and 3 inches of diameter. The calculating method of heat transfer in agitated jacketed vessels is applied to visualize the relationships. The effects of steam velocity on heat transfer, heating duration, and pressure drop respectively are polynomials of order 2, power, and polynomials of order 2 with an average R^2 close to 1. The greater R^2, the better the relationship between two variables, according to the equation. The 120° half-pipe jacket performance will be highly effective, with 1774 W, 2.1 minutes heating duration, 8.94 kPa pressure drop if the steam velocity is 10.50 m/s with 2.5 inches pipe diameter.

INTRODUCTION

Double jacket mixing tanks are widely used in the food, beverage and pharmaceutical industries. This mixer focuses on mixing where the temperature needs to be maintained using a jacket. The material used in the tank and jacket must meet GMP (Good Manufacturing Practices) standard, such as SS316L or SS304 [1].

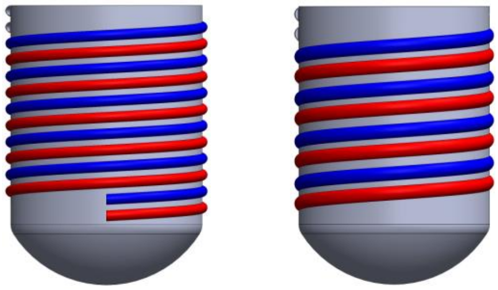
Mixing process for liquid drug in a double jacket mixing tank begins with putting the ingredients into the tank, the steam as a heating fluid flows inside the jacket to heat the ingredients up to the mixing temperature. Mixing process is started by operating the paddle mixer that generates radial and tangential flows with a slight axial motion for 4 minutes [2]. Cooling fluid (cooling water) flows inside the jacket to absorb heat from the liquid drug and the tank after the mixing process is complete.

The types of jackets commonly used in double jacket mixing tanks are conventional, dimple, and half-pipe jacket. Conventional and dimples jackets have one chamber while half-pipes have multi-zone passages through which the heating and cooling fluids flow.

(a) corrosion (b) cracks and fractures

Figure 1. Dimple Jacket Damages [3]

Conventional jacket is easier to produce and relatively inexpensive, but it is not resistant to high temperature and pressure. The dimple jacket has good heat transfer but is susceptible to damage due to extreme temperature fluctuations due to the use of alternating heating and cooling fluids in a short time. The examples of damages to the dimple jacket are shown in **Figure 1**. While the half-pipe jacket is resistant to high temperature and pressure and has good structural strength, the production and installation costs are quite high [1], [4], [5]. With good structural strength, the half-pipe jacket was chosen to evaluate its heat transfer performance.



(a) 180° (b) 120°

Figure 2. Half-Pipe Jacket

A half-pipe jacket consists of a split pipe that is wound around the tank. **Figure 2** shows a half-pipe jacket with steam heating fluid (red) and cooling water cooling fluid (blue). The half-pipe jacket has good heat transfer characteristics because the fluid velocity and turbulence are quite high, with a recommended fluid velocity of v ≥ 2.3 m/s [6].

A half-pipe jacket's central angle is typically 120° and 180°. The 120° half-pipe jacket tends to have a greater pressure drop than the 180° half-pipe jacket because the smaller angle results in a more compressed construction shape, so the fluid flow experiences more resistance and turbulence. A half-pipe jacket with a central angle of less than 180° can improve heat transfer and show better heat transfer performance compared to a central angle of 180° with the same flow rate [7] [8]. With a better heat transfer, the 120° half-pipe jacket tends to have a shorter duration.

The idea of heat transfer between the jacket and the mixer tank is the same as that of heat transfer in a heat exchanger, where convection and conduction are the dominants. Geometrical patterns and three dimensionless quantities, namely the fluid's Reynolds number, Nusselt number, and Prandtl number, have a significant impact on convection heat transfer [4].

Heat transfer is impacted by pitch (half-pipe distance), overlapping, and Reynolds number, all of which increase with pipe diameter [9]. The pressure drop and Nusselt number both rise as the turbulence inside the pipe intensifies [10][11]. As the fluid moves farther, the pressure drops. The pressure dramatically decreases at pipe bends [12].

The rate of heat transfer increases as the heat load in the form of mass flow increases [13] [14]. With rising fluid velocity, the heat exchanger's efficiency similarly rises [15]. However, after reaching the maximum value, the effectiveness decreases [16]. Reduced pipe winding will result in an increase in the average Nusselt number from both sides of the heat exchanger, which will boost heat transfer [17]. Energy is lost during the heat transfer process due to the fluid's high velocity and the numerous bends [18].

Because steam velocity impacts fluid performance and the half-pipe jacket exhibits more structural strength than the dimple jacket, this study will examine how speed affects steam performance in the half-pipe jacket. The effect of velocity on steam performance can be used as a consideration in designing half-pipe jackets for double-jacket mixing tanks.

METHODS

The research was conducted using a mixer tank on a double jacket mixing tank. The calculation of the heat transfer coefficient on the side of the tank requires the parameters of the tank and the liquid in the tank.

The required tank parameters are geometry, wall thickness, and thermal conductivity. The required parameters of the liquid in the tank are the initial temperature and mixing temperature, density, viscosity, heat capacity, thermal conductivity, and fouling factor of the liquid drug (**Table 1**).

The required parameters to calculate the heat transfer coefficient, heating duration, and pressure drop on the half-pipe jacket are the central angle, pipe diameter, number of turns, inlet and outlet temperatures, density, viscosity, heat capacity, thermal conductivity, and fouling factor of the steam (**Table 2**).

Table 1. Parameters of Tank and Liquid Drug

Parameter	Value	Unit
Tank Capacity	1250	litter
Head	315	mm
Bottom	315	mm
TL-TL Length	1300	mm
Thickness	8	mm
Inside Diameter	1100	mm
Material	Stainless Steel 316L	
Initial Temperature	30	°C
Mixing Temperature	80	°C
Drug Liquid Density	1250	kg/m³
Liquid Drug Viscosity	1000	cPs
Liquid Drug Heat Capacity	6000	J/kg°C
Liquid Drug Thermal Conductivity	9.54	W/(m.°C)
Liquid Drug Fouling Factor	0.0006	(m².°C)/W
Liquid Drug Volume	900	l/batch

Commonly used diameters for half-pipe jacket range from 2 to 3 inches, while the spacing between half pipes is generally in the range of ¾ to 1½ inches (20 to 40 mm) [1].

Table 2. Half-Pipe Jacket Parameters

Parameter	Value	Unit
Central Angel	120	°
Pitch between Half Pipes	35	mm
Material	Stainless Steel 304	
Inlet Temperature	90	°C
Outlet Temperature	60	°C
Steam Density	0.246	kg/m³
Steam Viscosity	0.0111	cPs
Steam Heat Capacity	1.957	kJ/kg°C
Steam Thermal Conductivity	0.0227	W/(m.°C)
Steam Fouling Factor	0.00009	(m².°C)/W
Pipe Diameter (inch)	**Number of Turns**	
2	7	
2.5	6	
3	5	

The heat transfer rate Q is proportional to the surface area (A) which depends on the system geometry, the temperature difference (ΔT) which depends on the process operating conditions and the heating or cooling fluid, as well as the overall heat transfer coefficient (U).

In a double jacket mixing tank, mixing only has an impact on the heat transfer coefficient on the tank side (hi), which is influenced by the impeller's type, geometry, position, level of turbulence, and reaction to liquid drug ingredients. The thickness and type of material used have an impact on the heat transfer coefficient on the wall of the mixer tank (hw). The type of fluid used and the flow velocity have an impact on the heat transfer coefficient on the jacket side (ho). Fouling that develops on either the jacket fluid side (ffo) or the process fluid side (ffi) can have a considerable impact on heat transfer.

Assuming the position of the impeller is at the midpoint of the tank diameter and the liquid drug ingredients do not generate heat when they react during the mixing process. Performance, heating duration, and pressure drop during heat transfer are determined using the calculations from Heat Transfer in Agitated Jacketed Vessels [19].

The heat transfer coefficient on the tank side (hi) is calculated using equation (1).

$$hi = \frac{Nu_i k}{D_t} \tag{1}$$

Where Nu_i is the Nusselt number on the process side, k is the fluid thermal conductivity (W/m.°C), and D_t is the inside diameter of the tank (m).

The heat transfer coefficient on the mixer tank wall (hw) is calculated using equation (2).

$$h_w = \frac{k_t}{T_t} \tag{2}$$

Where k_t is the thermal conductivity of the mixer tank wall (W/m. °C) and T_t is the thickness of the mixer tank wall (m).

The heat transfer coefficient on the jacket side (ho) is calculated using equation (3).

$$ho = \frac{Nu_o k}{D_e} \tag{3}$$

Where Nu_o is the Nusselt number on the half-pipe side, k is the fluid thermal conductivity W/(m.°C), and D_e is the half-pipe equivalent diameter (m).

The overall heat transfer coefficient (U) is calculated using equation (4).

$$\frac{1}{U} = \frac{1}{h_i} + ff_i + \frac{1}{h_w} + ff_o + \frac{1}{h_o} \quad (4)$$

Where h_i is the heat transfer coefficient on the tank side (W/m².°C), ff_i is the fouling factor of the fluid in the tank (m².°C /W), h_w is the heat transfer coefficient on the mixer tank wall (W/m².°C), ff_o is the fouling factor of the fluid in the jacket (m².°C /W), and h_o is the heat transfer coefficient on the jacket side (W/m².°C).

Heat transfer (Q) is calculated using equation (5).

$$Q = UA\Delta T \quad (5)$$

Where A is the heat transfer area (m²), U is the overall heat transfer coefficient (W/m².°C), and ΔT is the temperature difference (°C).

Heating duration (θ_{heat}) is calculated using equation (6).

$$\theta_{heat} = \left(\frac{mCp}{UA}\right) ln\left(\frac{T_{ui} - T_a}{T_{ui} - T_m}\right) \quad (6)$$

Where T_a is the initial temperature of the liquid drug (°C), T_m is the mixing temperature (°C), T_{ui} is the steam inlet temperature (°C), A is the heat transfer area (m²), Cp is the heat capacity of the liquid drug (kJ/kg°C), U is the overall heat transfer coefficient (W/m².°C), and m is the mass of the liquid drug in the tank (kg).

The pressure drop (ΔP) is calculated using equations (7) and (8).

$$\Delta P = 4f\left(\frac{L_c}{D_h}\right)\left(\frac{V^2}{2}\right) \quad (7)$$

$$f = 0.076 Re_o{}^{-0.25} + 0.0073\left(\frac{D_h}{D_c}\right)^{0.50} \pm 10\% \quad (8)$$

Where L_c is the length of the half-pipe (m), V is the steam velocity (m/s), f adalah friction factor, Re_o is the Reynolds number for the half-pipe jacket, D_c is the mean (centerline) diameter of the jacketed tank (m), and D_h is the hydraulic diameter of the half-pipe (m).

RESULT AND DISCUSSION

The fluid type, velocity, tank geometry, and jacket geometry all affect how well heat is transferred. The Reynolds number is determined as indicated in **Figure 3** using the same tank geometry and variations in pipe diameter and heating fluid velocity. The Reynolds number increases with both fluid velocity and pipe diameter.

Heat transfer happens by conduction in laminar flow (Re<2100). In order to maximize the efficiency of heat transfer through convection, the thermal boundary layer becomes thinner as the Reynolds number rises and fluid movement becomes more random [20].

The relationship between steam velocity and Reynolds number is linear, with R^2 equal to 1. R^2 refers to the Pearson correlation coefficient, which is a statistical measure that describes the strength and direction of the relationship between two variables. In the three diameters, it can be seen that the larger the diameter, the greater the slope of the line equation, so that the increase in speed causes a much greater increase in the Reynolds number.

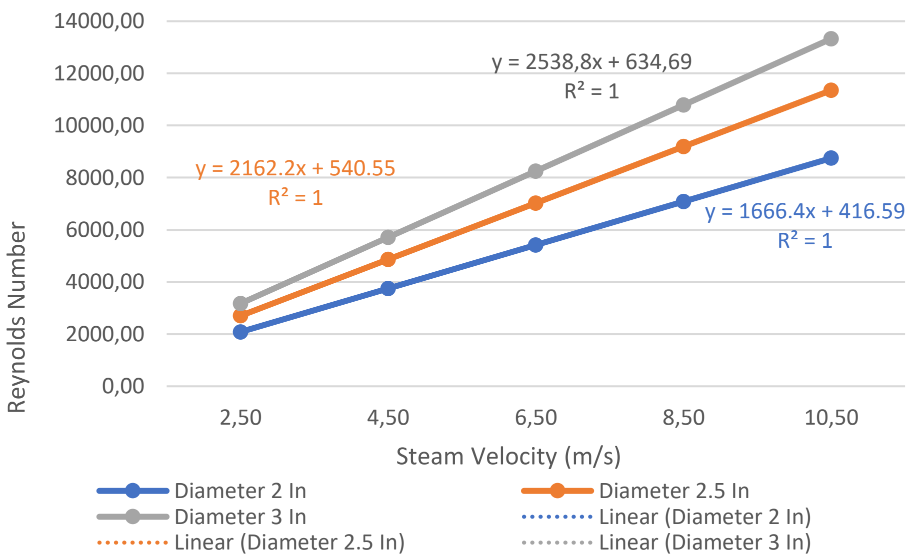


Figure 3. Effect of Steam Velocity on Reynolds Number on Half-Pipe Jacket

The heat transfer coefficient in the half-pipe jacket (ho) describes how well heat is transferred from the steam to the surrounding medium. The coefficient ho depends on the parameters of the steam. **Figure 4** shows that as the steam speed increases, ho will increase.

The relationship between steam velocity and ho is polynomial, with R^2 close to 1. The smaller the pipe diameter, the R^2 value in the above equation will be closer to 1. This shows better the variability of the data that can be explained by the regression model. This equation can be used to predict or estimate ho values outside the range of data used. If the steam speed increases, ho will increase in a certain pattern according to the polynomial equation. An increase in velocity of 2 m/s will result in an average increase in ho of 4.71 for a 2-inch pipe, 5.24 for a 2.5-inch pipe, and 5.06 for a 3-inch pipe.

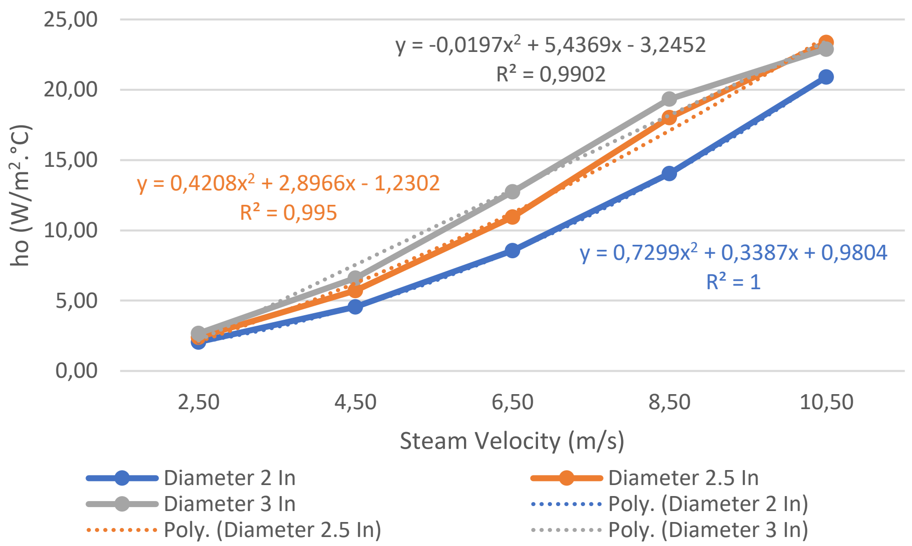


Figure 4. Effect of Steam Speed on the Heat Transfer Coefficient of the Half-Pipe Jacket

Figure 5 illustrates how steam velocity affects heat transfer efficiency. The rate of heat transfer between steam and the tank surface may rise with higher steam flow rates. The value of heat transfer is lower for a pipe with a diameter of 3 inches and a speed of 10.5 m/s than for a pipe of 2.5 inches in diameter.

The heat transfer is increased by larger pipe diameters and fewer turns. The fluid has a bigger surface area of contact with the jacket surface as pipe diameter increases. Due to the high amount of turbulence, the steam flow is uncontrolled, which results in a decreased heat transfer at a speed of 10.5 m/s in a 3 inch diameter pipe compared to a 2.5 inch diameter pipe.

Steam velocity and heat rate Q have a polynomial relationship with an R^2 close to 1. The average increase in heat rate Q with a 2 m/s speed increase is 357.95 W for a 2 inch pipe, 396.63 W for a 2.5 inch pipe, and 382.77 W for a 3 inch pipe.

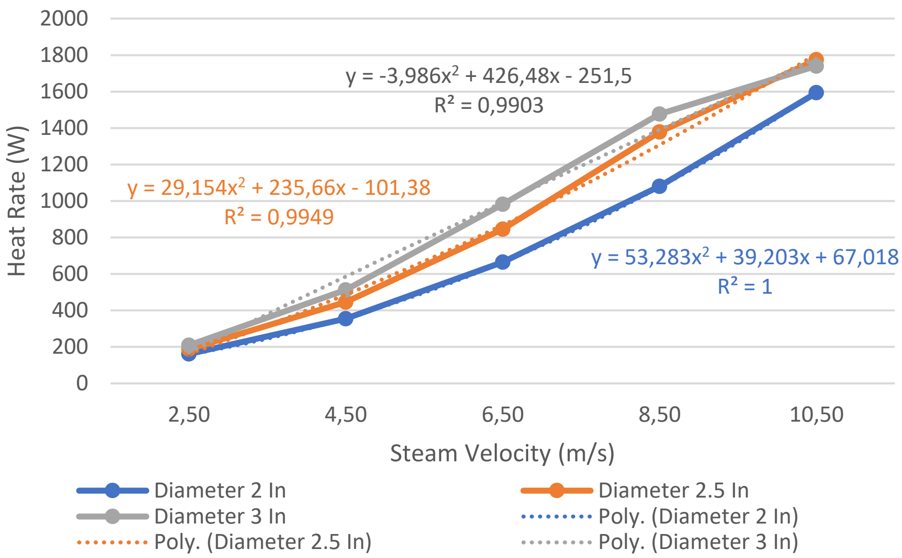


Figure 5. Effect of Steam Speed on the Heat Rate on the Half-Pipe Jacket

Figure 6 shows that the greater the steam speed, the shorter the heating duration. With an increase in steam speed, there is also an increase in heat transfer. Heat transfer refers to the transfer of energy from a heat source (steam) to a cooler medium (liquid drug). When efficient heat transfer occurs, heat energy will be absorbed more quickly by the cooler medium, so that the temperature of the medium rises more quickly. The same thing happened to the increase in diameter. The larger the pipe diameter, the greater the heat transfer, so the heating duration is shorter.

The relationship between steam speed and heating duration is power with R^2 close to 1. If the steam speed increases, the heating duration will decrease in a certain pattern according to the power equation. With an increase in speed of 2 m/s it will result in a decrease in average heating duration of 5.12 minutes for 2 inch pipes, 4.38 minutes for 2.5 inch pipes, and 3.88 minutes for 3 inch pipes.

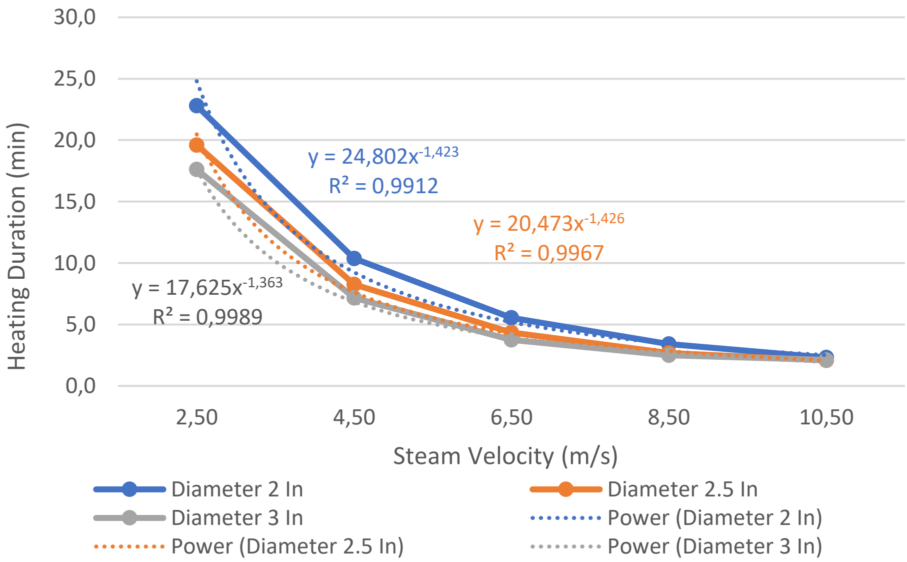


Figure 6. Effect of Steam Speed on the Heating Duration of the Half-Pipe Jacket

The longer the fluid flows, the pressure will decrease. **Figure 7** shows that an increase in steam speed causes an increase in pressure drop. As the speed increases, the Reynolds number increases, which indicates more turbulent flow. Turbulence affects the increase in frictional force, causing the pressure drop to increase.

Meanwhile, the larger the pipe diameter, the smaller the pressure drop.

This is because with a constant fluid flow velocity for each pipe, an increase in pipe diameter will reduce the frictional force between the fluid and the pipe surface, so that the pressure drop will be smaller.

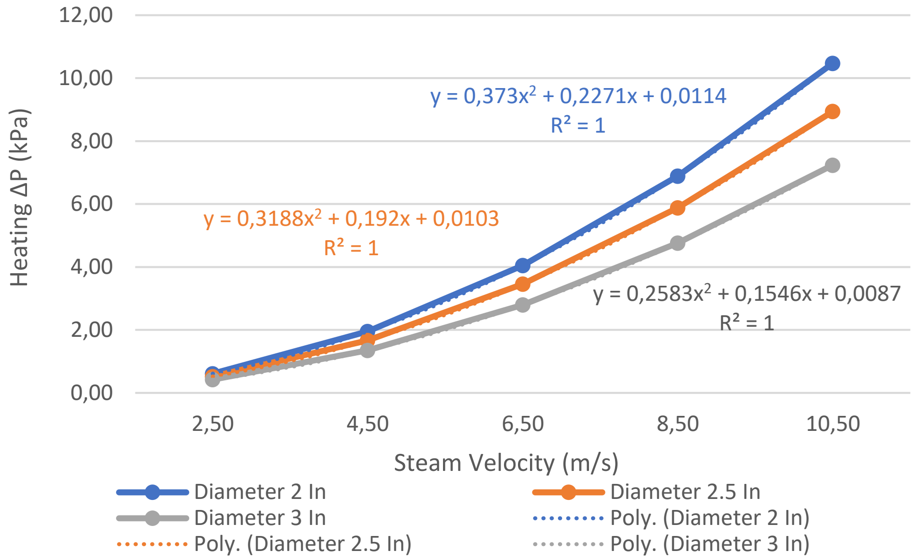


Figure 7. Effect of Steam Speed on the Heating Pressure Drop of the Half-Pipe Jacket

The relationship between steam velocity and pressure drop is polynomial, with R^2 equal to 1. If the steam speed increases with a constant pipe diameter, then the pressure drop will increase in a certain pattern according to the polynomial equation. With an increase in velocity of 2 m/s, it will produce an average pressure drop of 2.46 kPa for a 2-inch pipe, 2.10 kPa for a 2.5-inch pipe, and 1.70 kPa for a 3-inch pipe.

CONCLUSION

The use of a half-pipe jacket with optimal steam velocity in the double jacket mixing tank can have practical consequences that include heat transfer performances such as heat rate, duration, and pressure drop. Those can have an impact on improving product quality, reducing processing time, and increasing overall operational efficiency. The correlations between steam velocity and heat rate, heating time, and pressure drop were discovered from the velocity variation to be polynomials of order 2, power, and polynomials of order 2, respectively, for the three observed diameter sizes. If the steam speed is 10.50 m/s and the pipe diameter is 2.5 inches, the heat transfer performance of the half pipe casing will be highly effective (Q = 1774 W) with a heating period of 2.1 minutes and a pressure drop of 8.94 kPa.

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