Section A-Research paper
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Engineering study of water jacket system in place of a spiral heat exchanger at mining and mineral ore processing industry

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ABSTRACT

Mining and mineral processing plants are based on alkali leaching-based grinded ore processing with an operating capacity of several metric tons per day. Alkali leaching takes place inside pressurized autoclaves at a controlled temperature and pressure.

Heat reduction is a significant issue in mineral processing industries, and heat exchangers are incredibly useful for heat reduction. The heat exchanger is the main equipment for dissolution, chemical reaction, crystallization, distillation, fermentation, etc. Correct selection of heat exchangers is very important in process industries. Spiral heat exchangers are recognized as resourceful heat exchangers due to their compacted arrangement and elevated heat transfer effectiveness.

An estimation study was done for the probable length of stainless steel pipe required for a double pipe heat exchanger in place of existing heat exchangers with a water jacket around stainless steel pipeline for economic benefits of organization and use of continuously generated heated water for other useful purposes at the mineral processing plant.

Keywords: Spiral Heat Exchanger, Double Pipe Heat Exchanger, Autoclave, Mineral Processing, Film Resistance, Thermal Conductivity, Specific Heat.

1. INTRODUCTION

Many fluids are appropriate intended for a spiral heat exchanger solution i.e. fouling liquid with solids and fibers, wastewater, slurries, mixture with inert gas, cooling and heat improvement, vapor/liquid condenser, and vacuum condenser with inert gases [1]. The main benefits of the engineering study of water-jacketed double pipe heat exchanger system in place of the spiral heat exchanger at mining and mineral ore processing industry are as follows;

a. Capital benefits in terms of spiral heat exchanger replacement.
b. Reuse of generated heat from exothermic reactions.
c. Heated water generated through the water jacket may be used for flocculent preparation, which leads to improving further filtration efficiency.
d. Heated water helps in improving settling characteristics of leach belt filter spillage thickener.
e. Improved contact area between inner and outer pipe of the double tube heat exchanger.

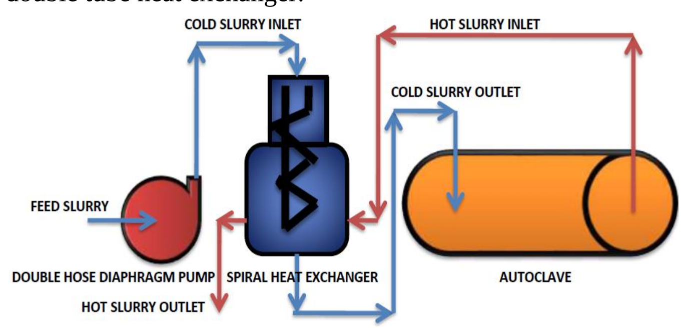

Figure 1. Schematic representation of existing heat exchanger system at mineral processing industries.

Several chemical reactions during alkali leaching inside autoclaves take place.

$$2UO_2 + O_2 \rightarrow 2UO_3 \quad (1)$$
$$UO_3 + 3Na_2CO_3 + H_2O \rightarrow Na_4UO_2(CO_3)_3 + 2NaOH \quad (2)$$
$$2FeS_2 + 7O_2 + 8Na_2CO_3 + 6H_2O \rightarrow 2Fe(OH)_2 + 4Na_2SO_4 + 8NaHCO_3 \quad (3)$$

Chemical reaction (3) is exothermic due to the pyrite content in the ore. The temperature may rise to 320°F due to it. Spiral heat exchangers as in figure 1 are used for preheating autoclave feed. Autoclave discharge slurry temperature helps in preheating the feed to recover the heat.

2. MATERIALS & METHODS

2.1 Existing spiral heat exchanger system at mineral processing industry

In figure 2, a schematic diagram of a spiral heat exchanger with routes of hot slurry (red paths) and routes of cold water

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(blue paths) are indicated. The routes of cold and hot fluids are separated with an SS316 metallic layer, and the heat exchange is done via indirect contact. For increasing the thermal efficiency of the heat exchanger, the inlet and outlet shapes are designed especially [2].

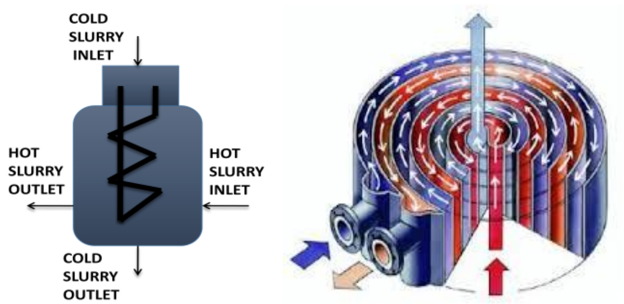

Figure 2. Flow diagram and schematic representation of existing heat exchanger at mineral processing industry [3].

2.2 Pipes dimensions and operating temperature details

Grinded ore slurry temperature is maintained at approximately 275°F (T_{Hin}) [4] inside the pressurized autoclave. Discharge passes through a 6-inch diameter stainless steel pipeline of schedule 40 (ANSI B36.10-1959_ASME). The slurry temperature is required to reduce up to 149°F (T_{Hout})[4] for feeding on leach belt filters. It was considered to have one water jacket pipe of schedule 40 and a diameter 8 inch round hot slurry stainless steel pipeline (figure 3). Input temperature of cold water was considered 105.8°F (T_{Cin})[4] which may raise to 226.4°F (T_{Cout}) [4] due to contact with hot slurry pipeline and good thermal insulation.

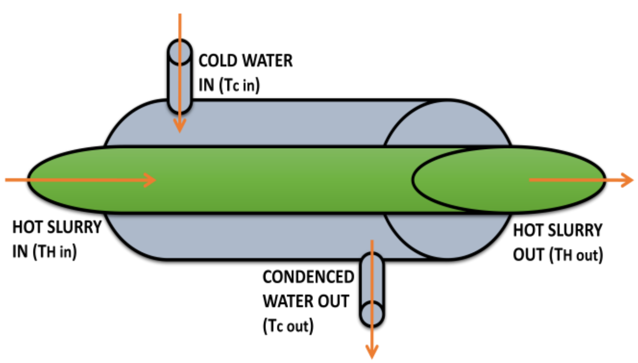

Figure 3. Proposed counterflow double pipe heat exchanger.

2.3 Logarithmic mean temperature difference

The logarithmic mean temperature difference is used to find the heat motivating energy for heat transfer in stream systems, notably in heat exchangers. The LMTD is a logarithmic average of the temperature difference between the hot slurry and cold water at each end of the double pipe exchanger. For a specified heat exchanger with a stable area and heat transfer coefficient, the larger the LMTD, the extra heat is transferred per unit time. The use of the LMTD arises directly from the investigation of a heat exchanger with a stable flow rate and liquid thermal property.

We believe that a model heat exchanger has two ends at which the hot and cold stream enter or way out on either side; then, the LMTD is defined by the logarithmic mean as follows:

$$\Delta T_{lm} = \frac{(T_{Hin}-T_{Cout})-(T_{Hout}-T_{Cin})}{ln\frac{(T_{Hin}-T_{Cout})}{(T_{Hout}-T_{Cin})}} \quad (1)$$

LMTD, ΔT_{lm} = 39.66 °F

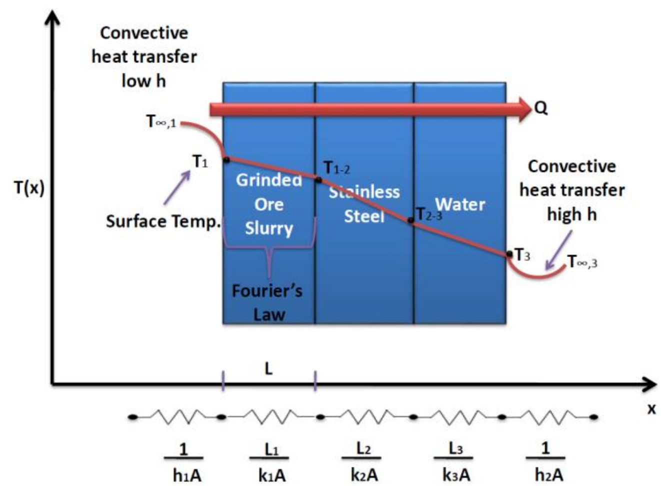

Figure 4. Internal, external, and conductive resistance representation using Fourier's law of heat conduction.

2.4 Prandtl Number for grinded ore slurry

It is a dimensionless parameter used in calculations of heat transfer coefficient between moving grinded ore slurry and a solid stainless steel pipe body. It was assumed that heat capacity, viscosity, and thermal conductivity are for grinded ore slurry of the mineral processing industry. Prandtl Number for grinded ore slurry may be defined as:

$$Pr = \frac{\mu C_P}{k} \quad (2)$$

Pr = 9.1904

2.5 Internal film resistance due to grinded ore slurry

It may be specified based on a thermal resistance arrangement intended for a cylindrical (or sphere-shaped, refer to figure 5) shell subjected to convection from both the internal and external sides. Internal film resistance suitable to grinded ore slurry is represented as,

$$R_{t\ inside\ convection} = \left(h_i \frac{A_i}{L}\right)^{-1} \quad (3)$$

Where A_i/L is defined as internal heat transfer area per unit length. Heat transfer coefficient, h_i for grinded ore slurry may be defined by Dittus-Boelter Equation no. (4) which represents Nusselt number (Nu),

$$Nu = h_i \frac{D_i}{k_b} = 0.023\ Re^{0.8}\ Pr^{0.3} \quad (4)$$

$$\text{Reynolds Number, } Re = \frac{\rho V D_{eq}}{\mu} \quad (5)$$

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Table 1. Parameters considered for estimation of Reynolds number of grinded ore slurry for existing operating conditions.

Sl.No.	Parameter	Unit	Symbol	Value
1	Density	lbm/ft^3	ρ	99.88
2	Volumetric flow rate	lb/hr	Q	130395
3	C/S area for flow	ft^2	A	0.20
4	Flow velocity	ft/sec	V	3.91
5	Viscosity	lbf-sec/ft^2	μ	0.0019
6	Pipe Diameter	ft	D_{eq}	0.50

Reynolds Number for grinded ore slurry was estimated to be 105667 using data of table 1.
Thermal conductivity of grinded ore slurry, k_b was considered 0.34 BTU/hr-ft-°F.
Prandtl number of grinded ore slurry was calculated as 9.19.
Heat transfer coefficient,
h_i = 310.60 BTU/hr-ft^2-°F
Heat transfer area per unit length,

$$\frac{A_i}{L} = \frac{\pi \ Di \ L}{L} \tag{6}$$

$\frac{A_i}{L}$ = 1.59 ft^2/ft
Inner film resistance for grinded ore slurry was calculated as 0.0020 hr.ft.°F/BTU.

2.6 Prandtl Number for water

It is a dimensionless factor used in calculations of heat transfer flanked by moving water and a solid stainless steel pipe body. It was assumed that heat capacity, viscosity, and thermal conductivity are for water. Prandtl Number for water may be defined as:

$$Pr = \frac{\mu C_P}{k}$$

Pr = 9.91[5]

2.7 External film resistance due to water

It may be defined based on a thermal resistance network for a cylindrical (or spherical, refer to figure 5) shell subjected to convection from both the inner and outer sides. External film resistance due to water is represented as,

$$R_{t \text{ outside convection}} = \left(h_0 \frac{A_0}{L}\right)^{-1} \tag{7}$$

Where A_o/L is defined as external heat transfer area per unit length. Heat transfer coefficient, h_0 for water may be defined by Dittus-Boelter Eq. no (8) which represents Nusselt number (Nu),

$$Nu = h_i \frac{D_i}{k_b} = 0.023 \ Re^{0.8} \ Pr^{0.4} \tag{8}$$

Table 2. Parameters considered for estimation of Reynolds number of water for existing operating conditions.

Sl.No.	Parameter	Unit	Symbol	Value
1	Density	lbm/ft^3	ρ	62.43
2	Volumetric flow rate	lb/hr	Q	130395.31
3	C/S area for flow	ft^2	A	0.11
4	Flow velocity	ft/sec	V	7.27
5	Viscosity	lbf-sec/ft^2	μ	0.0013
6	The hydraulic diameter of the annulus	ft	D_{eq}	0.11

Reynolds Number for liquid water was estimated to be 39510 using data from table 2.
Thermal conductivity of liquid water, k_b was considered 0.37 BTU/hr-ft-°F [5].
Prandtl number of liquid water was calculated 9.91.
Heat transfer coefficient,
h_i = 888.45 BTU/hr-ft^2-°F
Heat transfer area per unit length,
$\frac{A_i}{L}$ = 2.26 ft^2/ft
External film resistance for liquid water was calculated 0.0005 hr.ft.°F/BTU.

2.8 Conduction resistance due to stainless steel (SS316) pipeline

Conduction through cylindrical shells (e.g. pipes) can be calculated from the internal radius, r_i, the external radius, r_0, and thermal conductivity, k of pipe material (refer to figure 5). It may be defined as,

$$R_{t \text{ conduction}} = \frac{\ln r_0/r_i}{2\pi k} \tag{9}$$

Thermal conductivity, k of SS316 metal was considered 9.4 BTU/hr-ft-°F[5]
Conduction resistance due to stainless steel (SS316) pipeline was calculated 0.0006 hr-ft-°F/BTU.

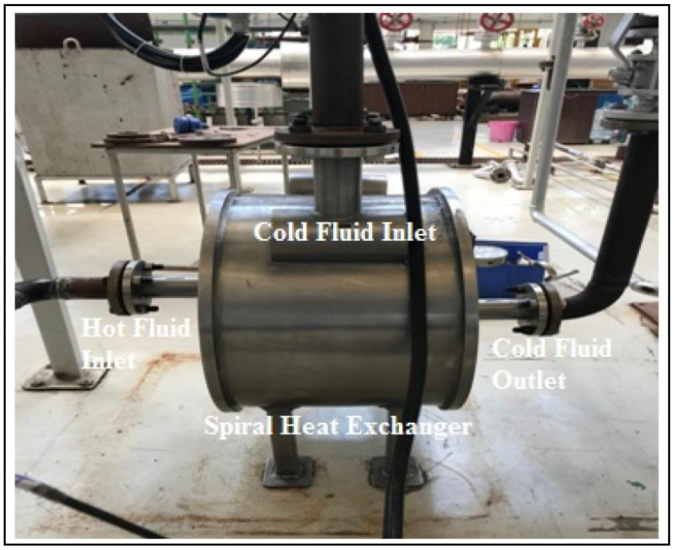

Figure 5. Spiral heat exchanger setup and directions of cold and hot fluid at pilot plant scale [6].

2.9 Overall resistance

The entire resistance of a component includes all of the resistances of the individual materials that compose it up as well as both the inner and exterior air-film resistance. Its units are the inverse of conductivity. It may be defined as the addition of internal film resistance due to grinded ore slurry, external film resistance due to liquid water, and conduction resistance due to stainless steel (SS316) pipeline.

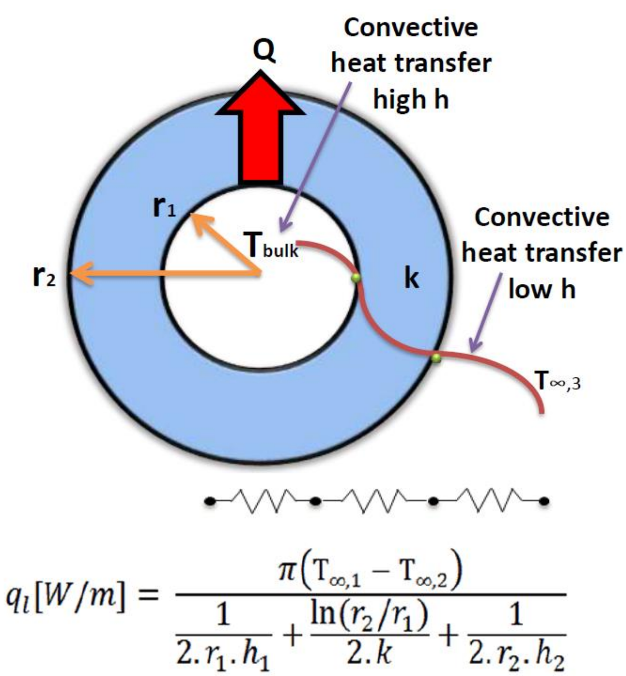

Figure 6. Heat transport due to warm grinded ore slurry and cold water using Newton's law of cooling and Fourier's law; apply for all material, apart from its situation (hard, fluid, or gas).

Using equations 3, 7, and 9, overall resistance ΣR may be defined by equation no 9,

$$U_0\frac{A_0}{L} = \left[\frac{1}{h_0\left(\frac{A_0}{L}\right)} + \frac{\ln r_0/r_i}{2\pi k} + \frac{1}{h_i\left(\frac{A_i}{L}\right)}\right]^{-1} = (\Sigma R)^{-1} \tag{10}$$

2.10 Heat transfer rate of liquid water

Heat exchanger calculation with the heat exchanger design equation involves an assessment for the heat transfer rate, Q, which can be calculated from the identified flow rate of one of the fluids, its heat capacity, and the requisite temperature alteration. Subsequent is the equation to be used

$$Q = m_c\, C_{pC}\, (T_{Cout} - T_{Cin}) \tag{11}$$

Table 3. Parameters considered for estimation of the heat transfer rate of liquid water for existing operating conditions.

Sl.No.	Parameter	Unit	Symbol	Value
1	Density	kg/m^3	ρ	1000
2	Volumetric flow rate	m^3/hr	Q	80
3	Mass flow rate	lb/hr	m_c	176369
4	Specific heat [5]	BTU/lb-°F	C_{pC}	1

2.11 Specific heat of grinded ore slurry

The specific heat is the quantity of warm through per unit mass essential towards increasing the hotness by one degree Fahrenheit. The relationship between warmth and temperature alter is generally articulated in the form is represented below where c is the specific heat.

$$Q = m_H\, C_{pH}\, (T_{Hin} - T_{Hout})$$
$$= m_c\, C_{pC}\, (T_{Cout} - T_{cin}) \tag{12}$$

Table 4. Parameters considered for estimation of specific heat of grinded ore slurry for existing operating conditions.

Sl.No.	Parameter	Unit	Symbol	Value
1	Density	kg/m^3	ρ	1600
2	Volumetric flow rate	m^3/hr	Q	80
3	Mass flow rate	lb/hr	m_H	282191.36
4	Specific heat	BTU/lb-°F	C_{pH}	0.59

3. RESULTS AND DISCUSSION

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An estimation study was done for the replacement of a spiral heat exchanger using stainless steel pipeline for decreasing grinded ore slurry temperature from approximately 275°F to 149°F.

Heat transfer rate of hot grinded ore slurry,

$$Q_h = U_o A_o \Delta T_{ln} \tag{13}$$

Heat transfer rate of hot grinded ore slurry per unit length,

$$\frac{Q_h}{L} = U_0 \frac{A_0}{L} \Delta T_{ln}$$

Where the value of LMTD (ΔT_{ln}) was calculated using equation number 1 and the value of $U_0 \frac{A_0}{L}$ was taken from equation number 10 using overall resistance ΣR.

Heat transfer rate per unit length,

$$\frac{Q_h}{L} = 32571 \text{ BTU/hr-ft}$$

Length of pipe required in place of heat exchanger = 199 meters.

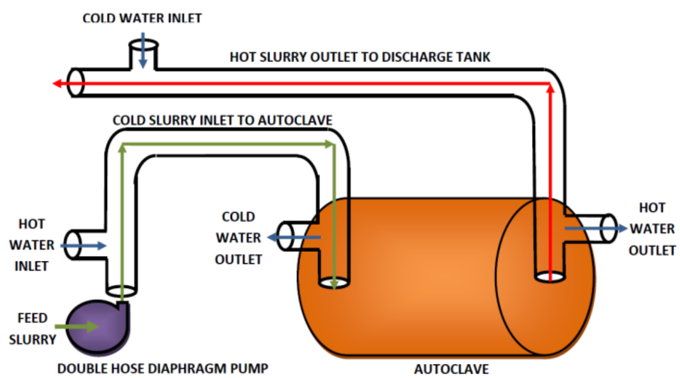

Figure 7. Schematic representation of modified heat exchanger system at the mineral processing plant.

4. CONCLUSIONS

a. A length of 200 meters approximately is reasonable to be fabricated as a serpentine double pipe heat exchanger.

b. The heat transfer coefficient for grinded ore slurry in a double pipe heat exchanger is calculated as 310.6 BTU/hr-ft^2°F.

c. based on industrial experience (figure 5), it is easy to do frequent cleaning and maintenance of double pipe heat exchanger as compared to a spiral heat exchanger [7].

d. Continuous water flow is required across the pipeline jacket to control the high temperature up to 165^{O}C.

e. based on industrial experience (figure 5), proper use of heated water needs to ensure in the continuous running plant because a sufficient amount of water generates during the process of temperature control for the grinded slurry.

f. Safety features should be proper before execution at the operation level by JSHA reports preparation [8].

g. based on industrial experience (figure 5), necessary turnings/edges may provide in the pipeline to accommodate the required length within the limited space site.

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NOMENCLATURE

T_{Hin}	Hot slurry inlet temperature	[°F]
T_{Hout}	Hot slurry outlet temperature	[°F]
T_{Cin}	Cold slurry inlet temperature	[°F]
T_{Cout}	Cold slurry outlet temperature	[°F]
ΔT_{lm}	The logarithmic mean temperature difference	[°F]
°F	Degree Fahrenheit	--
h	Heat transfer coefficient	[BTU/hr-ft^2-°F]
Pr	Prandtl number	--
R_t	Film resistance	[hr.ft.deg.F/BTU]
m_H	The mass flow rate of slurry	[lb/hr]
m_c	The mass flow rate of water	[lb/hr]
Cp_H	Specific heat of hot slurry	[BTU/lb-°F]
Cpc	Specific heat of cold water	[BTU/lb-°F]
Cp	Heat capacity	[BTU/lb-°F]
k	Thermal conductivity	[BTU/hr-ft-°F]
Nu	Nusselt number	--
D_i	Hydraulic diameter	[ft]
k_b	Thermal conductivity	[BTU/hr-ft-°F]
Re	Reynolds number	--
SS	Stainless steel	--
r_i	Internal radius	[ft]
r_0	External radius	[ft]
ΣR	Overall resistance	[hr.ft.°F/BTU]
U_o	Overall heat transfer coefficient	[BTU/hr-ft^2-°F]
Q	Heat transfer rate	[BTU/hr]
L	Length of pipe	[ft]

GREEK SYMBOLS

μ	= Viscosity	[lbf-sec/ft^2]

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