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Performance Evaluation and Optimization of a Two Horse Power Concentric Tube Heat Exchanger

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The aim of this research work was to improve the performance of a two horse power (2hp) shell and tube heat exchanger. The available area obtained from calculation is $3.77\times10^{-3}m^2$ and 383.75W/M²K. Overall heart transfer coefficient was obtained. The heat exchanger was satisfactory and consists of one pass copper tube of internal diameter 10mm and length 120mm. The shell length and internal diameter of the shell are 95mm and 60mm respectively. The concentric tube heat exchanger has a total length of 245mm and 136mm width. The hot fluid passes through the copper tube while the cold fluid move on the annulus made of mild steel. The results of the experiment shows that the heat was transferred from the hot fluid gradually move counter currently to the cold fluid in the same direction of flow. Mild steel was used for the construction of the shell while copper was used for the tube. The efficiency is 51.89% was obtained. This confirmed that the optimized equipment is more efficient than initial machine performance efficiency of 40.76%. Significantly, this equipment is of great need when vaporized liquid must be recovered back as liquid at specified conditions and also control the flow of thermal energy between two terminals.

Keywords: Performance evaluation; optimization of a two horse power concentric tube heat exchanger.

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1. INTRODUCTION

Heat exchanger is a device used to implement the exchange of heat between two fluids at different temperature and separated by a wall occurs in many engineering application. Also it is a machine which enhances the exchange of heat transfer between two or more fluid. The fluid can be separated by a solid wall to prevent it's from direct content with one another in the process. Heat exchangers are used for both cooling and heating processes [1,2]. Heat exchangers are used in both cooling and heating processes [2,3].

The fluid that takes in heat is known as the cooler, while the fluid that gives out heat is called heater. In a heat exchanger, the temperature of fluid changes as it passes through the exchanger and hence the temperature of the dividing wall between the fluids changes as the differences in the length of the exchanger [4]. The device (heat exchanger) are widely used in space heating, refrigeration, air conditioning, power stations, chemical plants, petrochemical plant, petroleum refineries, and natural gas processing and sewage treatment [5].

Heat exchanger is commonly an internal combustion engine in which a circulating fluid known as engine coolant flows through a radiant coils and air flow past the coils, which the coolant mixed with the incoming air. A heat sink is another example of preside heat exchanger that transfer the heat generated by an electronic or a mechanical device to a fluid medium, often air or a liquid coolant, where it is dissipated away from the device, thereby allowing regulation of the devices temperature [6,7]. There is urgent need for heat transfer equipment such as a heat exchanger in the laboratory to carry out experiment on heat transfer. The work done by the previous students is quite commendable, however, there is a need to optimize the design and construction work so that the equipment will meet the required needs of efficient heat transfer, satisfactory data display and durability [8]. In the chemical engineering sector, the most important aim is to control the flow of thermal energy between two terminals of any plant. It will be an economic disaster and subsequently a bad business for a chemical process in industry to operate under the conditions of persistent heat losses. As a remedy for this, heat transfer equipment such as heat exchanger becomes a necessity. In addition, working knowledge of heat transfer equipment to under-graduate student will be great compliment as it will navigate their ways through the industrial world [9]. Therefore, the design and fabrication of a two hose (2lp) concentric tube heat exchanger for the training of students of the department of chemical engineering is a step in the right direction [10].

2. MATERIALS AND MATHODOLOGY

2.1 Materials

The materials that were used in the design work include:

I. Heater: This is an electrical instrument that was used to heat water in the aquarium. It consists of an electric coil covered in ceramics. It was suspended inside the water and used to maintain a constant water temperature inside the heat exchanger tank.
II. Electrode: this is a material that was used to fuse two work pieces together.
III. Connector: This is an electro-mechanical device that was used to join electrical parts. This consisted of plugs and jacks.
IV. Connecting cables: They are the optional solution that was used to put all common sensors, liquid, vision and ID-product into operation.
V. Cutting disc: There are tools that were used for cutting different types of metals.
VI. Abrasive: This is a material that was used to shape or finish a work piece through rubbing which lead to part of the work piece being worn away by friction.
VII. Paint: The assembled part was coated with oil paint to make it have luster as well as it avoids corrosion attack on the equipment. The painting was made using a sprayer machine.
VIII. Steel tube: It's a pipe with tubular section or hollow cylinder usually but not necessarily of circular cross section that was used to convey substances which can flow liquids.
IX. Brass rod: This is fabricated from any alloy of copper and varying level of zincs, sometimes with additional elements for special properties.
X. Control panel: A board or panel incorporating controls for the operation of a machine or it's a flat often vertical area where control or monitoring instrument are displayed.
XI. Thermometer: This is a device that was used to measure the temperature or temperature gradient.

XII. Electric pump: This is a device which was used to provide energy to the fluid in a fluid element. It also assists to increase the pressure energy. Pumps are used to transport fluid by the conversion of rotational kinetics energy to the hydro-dynamic energy of the fluid flow.

XIII. Reservoir: This is storage tank which the fluid or water used in the operation was stored for future use.

XIV. Copper tube: this is a pipe will tubule section or hollow cylinder that was used to convey the liquid substances or fluid.

2.2 Sources of Materials

Many factors were put into consideration before selecting the right material for the fabrication. These factors includes; resistance to corrosion, cost of material acquisition, mechanical and electrical properties. Most of the materials used in the fabrication were obtained from Onitsha main market in Anambra state, Nigeria.

2.3 Chart 1

Chart 1. Equipment's used in the improvement of shell and tube heat exchanger

S/n	Items	Type
1	Punch roil machine	W12-23;2000
2	Bench shear	Model: T27140
3	Angle grinder	Model: G420
4	Pedestal drill	Bosch:710W
5	Portable drill	U2000PK
6	Hack saw	Model: H12050
7	Measuring tape	Stanley 35m-425
8	Metal arc welding machine	Model: 240V-750W

2.4 Fabrication Methodology

2.4.1 Marking out (Dimension Specification)

The required dimension of the shell and tube heat exchanger was marked out on the flat sheet of the mild steel using a scriber, steel ruler, measuring tape, chalk and divider [11]. The dimension marked out includes the inner and outer diameters.

2.4.2 Cutting

Having completed the marking out of the specified dimensions, the flat sheet (mild steel) was cut into the required dimensions. The equipment used in achieving this operation was guillotine, shearing machine, a bench shear machine, angle grinder and chisel.

2.4.3 Welding

Metal are welding was used due to the superiority of the weld and the increased speed of manipulation. They are stroke between a carbon electrode and the work itself so that the heat generated melts the surface of the weld. Weld meal was supplied from the filter rod [12]. The end of this rod meets and deposit on the joint, whilst at the same time heat generated melts the edges of the work.

The rolled ends of the sheet for the shell were welded to give the cylindrical shape of the containing vessels. The circular sheet for the base was joint to the cylindrical shell by welding it together.

2.4.4 Attrition

This operation involves the process of obtaining the required shape in a fashionable manner. The rough edges of the cut material and the welded area was made smooth with the aid of band files and angle grinder.

2.4.5 Assembling of Parts

The tube of the heat exchanger was inserted into the shell and welded. The shell was placed in the frame and tightened with bolt and nuts. The reservoir (hot and cold water) were placed and welded on top of the frame. The pipe was connected to shell and reservoir. Thermometers were attached to the shell and pipes respectively. The heat exchanger was painted and later tested to observe its efficiency [13].

2.4.6 Painting

The assembled parts were with aluminum paints to make it have luster as well as to avoid corrosion attack on the equipment. Painting was applied twice on the surface in order to ensure proper coating and surface protection against corrosion.

2.5 Cost Analysis

The costing of this project (performance evaluation and optimization of a concentric tube heat exchanger) was done in direct connection with all that was put into the attainment of the complete work.

For a defiled estimate, the costing is divided into material cost and labour cost while miscellaneous expenses made were neglected.

2.5.1 Material cost

Chart 2. The material cost was based on the actual market price of all the materials put into improvement of fabrication work

S/N	Component quality	Cost (₦)
1	Super glue	700
2	Pvc bond	2000
3	Plastic storage tank	6000
4	Gate valves	1600
5	Electrode	2200
6	Cutting disc	1000
7	Brass rod	2500
8	Pipe	2500
9	Pump (2hp)	28,000
10	Diesel (20 litres)	3500
11	Transportation	15,000
12	Labour	35,000
	Total	₦100,000

2.6 Mode of Operation of the Equipment (Machine)

The fluid was introduced into the reservoir and the pump was turned on in order to pump the fluid into the hot and cold fluid tank. The heater was switched on to heat up the fluid (water) gradually to 100^0C. The outlet valves of the hot water were half opened and same was done to the valves that controlled the cold water and were made to flow in counter current direction [14,15]. The thermometer reading was taken at entry and at steady flow; the temperature of the exit fluid was also taken.

3. RESULTS AND DISCUSSION

3.1 Result from Experiment

Chart 3.

For counter current flow

Flow pattern	Hot fluid inlet temperature °C	Hot fluid outlet temperature °C	cold fluid inlet temperature °C	Cold fluid outlet temperature °C
Reading	100	40	25	75

For parallel flow

Flow pattern	Hot fluid inlet temperature °C	Hot fluid outlet temperature °C	cold fluid inlet temperature °C	Cold fluid outlet temperature °C
Reading	80	40	30	50

3.2 Discussion of Result

In this work, the reservoir(hot and cold water) with a diameter 22mm, height 53mm and volume $0.025m^3$ (25litres) was used. The tube was made of copper with a dimension 10mm and 12mm internal and external diameter respectively and of length 120mm was used. The shell was made of mild steel with a diameter 60mm and length 95mm.

Four gate valves were used to control the flow pattern in the equipment (machine). The hot fluid (water) was introduced into the tube while the cold fluid (water) was flowing through the shell.

From the results obtained in the counter current flow; the hot fluid inlet and outlet temperature was 100°C and 40°C while the cold fluid inlet and outlet temperature are 25°C and 75°C respectively.

The result obtained in the experiment showed that the decrease in the outlet temperature of a hot fluid result in the increase of the outlet temperature of a cold fluid. Therefore, heat was absorbed in the exchange of flow in the process [16].

The overall heat transfer coefficient of the tube was 397.5W/M^2 °C. the temperature of the tube was 70°C and the volumetric and mass flow rates of the tubes are 2.506x10^{-8} M^3/S and 2.468x10^{-8} kg/S respectively.

The overall heat transfer coefficient of the shell was 370W/ M^2 °C, temperature of the shell was 500c and the volumetric mass flow rate of the shell are 7.3x10^{-8} M^3/S and 7.228x10^{-5} kg/S respectively. The variation in the values of the shell and tube above depends on the diameter [17].

Based on the performance test conducted on the improved heat exchanger with one pass shell and tube structure operated by a two horse power (2Hp) surface pump, the thermal efficiency of 51.89% was obtained [18]. This confirmed that the optimized equipment is more efficient than the initial machine performance efficiency of 40.78%

4. CONCLUSION

A concentric tube heat exchanger was improved and tested. This is to enhance the efficient heat transfer, satisfactory data display and durability. From the results obtained, the heat exchanger proved to be more efficient when the temperature of the hot fluid (water) dropped from 100^{0}C to 60^{0}C showing a moderate heat transfer rate. The aim of the design was met as heat was gained by the cold fluid (water) in the course of the process. The increase in the number of passes from one to five was essential in achieving maximum efficiency in the rate of heat transfer.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Design calculation for a concentric tube heat exchanger

Duty: 2 horse power

1 horse power= 746watts

2 horse power= 2(746)= 1492Watts

Heat load, Q= 1492J/s(Watts).

The fluids are water; one is cooling water and the other is hot water.

Fliud allocation for a counter current flow.

Tube side:

Heating water (hot water) at 100°C and leaving at 40°C

Shell side:

Cooling water at 25°C and leaving at 75°C.

Fluid allocation for a co-current flow.

Tube side:

Heating water (hot water) at 80^{0}C and leaving at 40°C

Shell side:

Cooling water at 30^{0}C and leaving at 50°C.

Log mean temperature difference Tm is given by:

$$\Delta Tm = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$$

(Sinott and towler,2013).

For parallel flow

$$\Delta T_2 = T_{h2} - T_{c2}$$

$$\Delta T_1 = T_{h1} - T_{c1}$$

$$\Delta Tm = \frac{(T_{h1} - T_{c1}) - (T_{h2} - T_{c2})}{\ln \frac{(T_{h1} - T_{c1})}{(T_{h2} - T_{c2})}}$$

Tm= $\underline{(40-50)-(80-30)}$

$\ln \frac{(40-50)}{(80-30)}$

$\frac{-10+50}{\ln \frac{-10}{50}}$

$\frac{40}{\ln(0.2)} = -24.85$

Tm= -25°C

For Counter current flow

$\Delta T_2 = T_{h2} - T_{c1}$

$\Delta T_1 = T_{h1} - T_{c2}$

$\Delta Tm = \frac{(T_{h2}-T_{c1})-(T_{h1}-T_{c2})}{\ln \frac{(T_{h2}-T_{c1})}{(T_{h1}-T_{c2})}}$

Where,

Tm= Log mean temperature difference
T_{h2} = Hot fluid outlet temperature
T_{h1} = Hot fluid inlet temperature
T_{c2} = Cold fluid outlet temperature
T_{c1} = cold fluid inlet temperature

$Tm = \frac{(100-75)-(40-25)}{\ln \frac{(100-75)}{(40-25)}} = \frac{25-15}{\ln(25/15)}$

$= \frac{10}{\ln(1.667)}$

Tm=19.58

$Tm = 20^0C$

The thermal efficiency of a concentric tube heat exchanger is given by:

$$\eta = [(\frac{1-\varepsilon 1 Cr}{1-\varepsilon 1})^n - 1] - [(\frac{1-\varepsilon 1 Cr}{1-\varepsilon 1}) - Cr]^{-1}$$

Where η is the efficiency of heat exchanger with one pass shell and tube structure.

$$\varepsilon_1 = 2[1 + Cr + (1 + Cr^2)\ ½ \times \frac{1+\exp[-(NTU)(1+Cr2)½]}{1-\exp[-(NTU)(1+Cr2)½]}]^{-1}$$

Where NTU is the number of transfer units and is equal to:

$$NTU = \frac{U_A}{C_{min}}$$

$C_{min} = C_{cf} = C_{pcf}M^*$

C_{pcf}= specific heat capacity for cold fluid (water)= $4.18 \times 10^3 J/kg^0C$ (Ray and Cavin, 2013)

$Cr = \frac{C_{min}}{C_{max}}$ = Capacity ratio

$C_{max} = C_{hf} = M^*C_{phf}$

C_{phf} = Specific heat capacity for hot fluid (water)= $4.18 \times 10^3 J/kg^0C$ (Ray and Cavin, 2013)

U= Overall average heat transfer coefficient

$= \frac{U_t + U_s}{2}$

Where,

$U_t = \frac{340 + 455}{2} = 397.5 W/M^2K$

U_t = Overall heat transfer coefficient for tube which is made of copper material.

$U_s = \frac{340 + 400}{2} = 370 W/M^2K$

U_s = Overall heat transfer coefficient of shell which is made of mild steel.

Therefore,

$U = \frac{U_t + U_s}{2} = \frac{397.5 + 370}{2} = 383.75 W/M^2K$

The density of water at various temperature are given below (Ray and Cavin,2013):

$T(^0C)$	40	50	70
$\rho(kgM^{-3})$	992.8	990.1	?

Using Extrapolation to find ρ_{70^0C}

$\rho_{50} = \rho_{40} + \frac{50-40}{70-40}(\rho_{70} - \rho_{40})$

$\rho_{50} = \rho_{40} + \frac{10}{30}(\rho_{70} - \rho_{40})$

$\rho_{50} = \rho_{40} + {}^1/_3(\rho_{70} - \rho_{40})$

$\rho_{50} - \rho_{40} = {}^1/_3(\rho_{70} - \rho_{40})$

$3(\rho_{50} - \rho_{40}) = \rho_{70} - \rho_{40}$

$\rho_{70} = \rho_{40} + 3(\rho_{50} - \rho_{40})$

992.8+3(990.1-992.8)

992.8-8.1

$\rho_{70^0C} = 984.7 kgM^{-3}$

Mass flow rates

Tube:

$M^*_t = \rho_t v_t$

Where,

$V_t = \frac{\pi D^2 L}{4t}$

Diameter of the tank, D = 22mm=0.022m

Length of the tank, L=52mm=0.053m

Time of flow in the tube,t =804sec

$$V_t = \frac{(3.142)(0.022)^2(0.053)}{(4)(804)}$$

$=2.506 \times 10^{-8}\ m^3/s$

$M^*_t = \rho_t v_t = 984.7 \times 2.506 \times 10^{-8}$ kg/s

$=2.468 \times 10^{-5}$ kg/s

$C_{phf}=4.18 \times 10^3 J/kg^0C$ (Ray and Cavin,2013).

$C_{hf} = M^*_t\ Cphf = 2.468 \times 10^{-5} \times 4.18 \times 10^3$
$=10.32 \times 10^{-2}$

$C_{max} =0.1032 J/s^0C$

Shell temperature is 50^0c

$C_{min} = M^*_s\ C_{cf}$
$M^*_s = \rho_s v_s$
$$V_s = \frac{\pi D^2 L}{4t}$$

Where,

Diameter of the tank, D = 22mm=0.022m
Length of the tank, L=52mm=0.053m
Time of flow in the shell,t =276sec

$$V_s = \frac{(3.142)(0.022)^2(0.053)}{(4)(276)}$$

$=7.3 \times 10^{-8}\ m^3/s$

$M^*_s = \rho_s v_s = 990.1 \times 7.3 \times 10^{-8}$ kg/s

$=7.228 \times 10^{-5}$ kg/s

$C_{pcf}=4.18 \times 10^3 J/kg^0C$ (Ray and Cavin,2013).

$C_{cf} = M^*_s\ Cpcf = 7.228 \times 10^{-5} \times 4.18 \times 10^3$

$=30.21 \times 10^{-2}$

$C_{min} =0.3021 J/s^0C$

$$\text{Capacity ratio, } Cr = \frac{Cmin}{Cmax} = \frac{0.3021}{0.1032}$$

=2.927

NTU = $\frac{U_A}{C_{min}}$

Where,

A= 2πrh
= 2πD/2L
= πDL

The area, A is the area of curve surface of the tube where heat transfer takes place

Diameter of the tube, D = 10mm=0.01m

Length of the tube, L=120mm=0.12m

A = πDL = (3.142)(0.01)(0.12)
=3.77×10^{-3} M^2

Therefore,

$$NTU = \frac{UA}{C_{min}} = \frac{(397.50)(3.79\times10^{-3})}{(0.3021)}$$

= 4.9605Ws/J

$$\varepsilon1=2[1+2.927+(1+2.927)^{½}\times\frac{1+\exp[-(4.9605)(1+2.927^{\wedge}2)^{\wedge}½]}{1-\exp[-(4.9605)(1+2.927^{\wedge}2)^{\wedge}½]}]^{-1}$$
$$=2[3.927+1.982\times\frac{1+\exp[-15.34]}{1-\exp[-15.34]}]^{-1}$$
$$=2[5.909\times\frac{1+2.177\times10^{\wedge}-7}{1-2.177\times10^{\wedge}-7}]^{-1}$$

ε_1=0.338

$$\eta = [(\frac{1-\varepsilon1Cr}{1-\varepsilon1})^n-1]-[(\frac{1-\varepsilon1Cr}{1-\varepsilon1})-Cr]^{-1}$$

$$\eta = [(\frac{1-(0.338)(2.927}{1-0.338})^1-1]-[(\frac{1-(0.338)(2.927)}{1-0.338})-2.927]^{-1}$$
$$=((\frac{0.0107}{0.662})-1)-(\frac{0.0107}{0.662}-2.927)^{-1}$$
$$=[-0.984-(-2.9108)]^{-1}$$

$\eta=\frac{1}{1.927}$= 0.5189
η= 51.89%

Therefore, the efficiency is 51.89%.

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