Design and Development of a Small Heat Exchanger as Auxiliary Cooling System for Domestic and Industrial Applications

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Abstract— **The epileptic supply of power from the national grid in Nigeria has made many industries to engage Internal Combustion Engine generators as alternative to providing energy required for production. The excessive use of these machines has mostly altered their effective performance, thereby necessitating more frequent maintenance or repair than recommended by the manufacturers. Frequent break-downs of these machines reduce rate of production of these industries and by extension, this adversely affects the economy development of the country. A known engineering enterprise in Kano; North West region of Nigeria due to the same factor stated above, subjected her 30 kva generator to run almost throughout the working hours of the week. Initially, the generator run perfectly within the manufacturer recommended 100 hours of operation before conducting maintenance works. After sometime, due to excessive use, the generator hardly met half the required service hours before overheating and this resulted in frequent damage of the gasket and repair of the valve outlets, consequently increased the cost of maintenance. A Small Tube and Shell Heat Exchanger with parallel/counter flow that would serve as an auxiliary cooling system for the radiator was designed and developed.**

K*eywords*— Flow, Fluid, Heat, Transfer and Tube.

S*ignificance*— The work would enhance local production and reduce down-time caused by frequent breakdown of generators used as alternative source of energy during manufacturing processes. In most instances, generators are designed as backup power source, but the reality in Nigeria and some other developing countries is that the supply from the main public utility power source is erratic. Hence, generators are usually run beyond the recommended cycle of use and this increases the rate of degradation significantly. This work would help manage a common fall out of the extended use by incorporating an additional cooling outlet to improve the efficiency of the cooling process. It would also reduce the rate of abandonment of domestic and industrial equipment due to non availability of parts or increased in maintenance cost by prolonging their service life.

I. INTRODUCTION

There are many applications where heat has to be transferred from higher temperature fluid to lower temperature fluid. The amount of heat transferred is a function of temperature differences and resistance in the heat transfer. A Heat Exchanger is a piece of equipment built for efficient heat transfer from one medium to another. The media may be separated by solid wall to prevent mixing or they may be in direct contact. It has various applications such as refrigeration, power plant, petroleum refineries, food processing plant, etc. The equipment can be in-built into a system such as radiator coils and air flows in automobile. There are different types of Heat Exchanger such as Plate and Shell, Adiabatic Wheel, Plate Fins, Tube and Shell, Spiral Heat Exchangers, etc.

There are primarily three classifications of Heat Exchanger; Parallel Flow Heat Exchanger allows the two fluids to enter the exchanger at the same end and travel in parallel to one another to the other side. Counter Flow type allows the fluids to enter the exchanger at the other side from opposite ends. Reference [1] reveals that the Counter Flow is currently the most efficient, because it can transfer the most heat from the medium due to the fact that the average temperature difference along any unit length is greater. Cross Flow Heat Exchanger allows fluids travel roughly perpendicular to one another through the exchanger.

For efficiency, Heat Exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing the resistance to fluid flow through the exchanger as in [7]. The operation of a cooling system of an internal combustion engine under an average working condition is optimized when the temperature of the cooling medium is at the range of $30^{O}C$ to $90^{O}C$ as in [6].

The Small Tube and Shell Heat Exchanger prototype developed is a Parallel/Counter Flow type to effectively reduce the temperature of the hot steam coming out from the engine from about $120^{O}C$ to about $70^{O}C$ before it enters into the radiator and optimizes the cooling effect at the radiator that enhances the performance of the generator and reduces the time of carrying out maintenance/repair on the engine.

II. EQUIPMENT DESCRIPTION

The machine consists of a set of ten straight tubes arranged successively at about angle of 30^{o} and held rigidly together by a set of five semi-circular baffles as shown in Fig 1. The tube bundle is enclosed in a shell with four openings to allow the inflow and outflow of the two media charged for the purpose of transfer of heat in each other. Pipes are arranged in series to channel the media into and out of the equipment.

Other gadgets for measurements of fluids' temperatures, pressures and flow directions like thermocouples, pressure gauges and directional flow valves respectively are incorporated. Pump and the tank/reservoir are mounted adjacent to each other at the base. The total assembly is supported on a main frame as shown in Fig 2. The steam fluid charged is hot water which is flowing from the engine via a pipe to the inner tubes of the Heat Exchanger. Heat is transferred in the Heat Exchanger from the hot steam to the cold water charged into the pipe connected to the shell annulus of the Heat Exchanger. The cooled hot steam is passed into the radiator where it is further cooled to required temperature that will cool the engine.

Temperature Sensors provided took the inlet and outlet temperatures of the hot steam and cooling agent (cold water). Also Pressure Gauges were connected to both the inlet and outlet of the hot steam to measure the pressure difference. A Directional Flow Valve regulates the flow of the fluids in required directions in the system.

When the steam and cold waters are admitted at the same end, a parallel flow is ensured and when the two fluids are admitted from opposite ends, counter flow is ensured. To enhance the efficiency of the machine, baffles are incorporated. Baffle directs the cold fluid across the outer surface of tube bundle to ensure a required heat transfer at a specific point, runs perpendicular to the shell to hold and prevent tubes from sagging over a long length as well to reduce effects of vibration of the tube. The cold water that cooled the hot fluid is collected in an opened reservoir where it is re-cooled by air and reintroduced back into the system for another cycle of cooling.

III. METHODOLOGY

The methodology that guided the project in the critical areas of developing a Heat Exchanger is discussed hereunder.

A. Design Considerations

The Heat Exchanger prototype was designed by taken the following considerations:

- Thermal feature of the medium to cool is just around $120^{o}C$ and this informed the adaption of a Small Tube and Shell Heat Exchanger.
- The material selected for the tube bundle is copper because it has good corrosion resistance, buckling strength to withstand over pressure in the shell and good thermal conductivity as in [5].
- Small internal diameter tube can actively transfer heat in the media as in [8], therefore small internal diameter tube is adapted and low fouling is suspected because the media do not contain much precipitation.
- The tube layout is triangular (arrangement of about angle of 30^{o}) because fluid flow is in more turbulence way in the pipe and greater heat could be transferred as in [4].
- The diameter and length of the tube adapted is 10mm and 1.2m respectively in order to ensure more heat transfer.
- Segmental semi-circular type of baffle is adapted for the equipment as recommended for Tube and Shell Heat Exchanger as in [3]
- The specific heat of fluid is 4.174Kj/Kg (water medium), Mass flow rate is 0.0194Kg/s and 0.0263Kg/s for hot steam and cold water respectively as in [2].
- The temperatures of the fluids charged into the Heat Exchanger are $120^{o}C$ and $30.5^{o}C$ for hot steam and cold water respectively (measured).
- The least efficiency adapted for the device is 75%

B. Design Analysis

1) Temperature of the Hot Steam leaving the Heat Exchanger (^{O}C): $\zeta = \frac{M_c\, c_p\,(T_{hi} - T_{ho})}{M_h\, c_p\,(T_{hi} - T_{ci})}$ …………………….. (i)

ζ = Efficiency

M_c = Mass flow rate of cold water (Kg/s)

M_h =Mass flow rate of hot steam (Kg/s)

C_p = Specific heat of fluid (KJ/Kg°C)

T_{hi} = Temperature of hot steam entering the heat exchanger (°C)

T_{ho} =Temperature of hot steam leaving the heat exchanger (°C)

T_{ci} = Temperature of cold water entering the heat exchanger (°C)

$$0.75 = \frac{0.0263\ x\ 4.174\ x\ (120 - T_{ho})}{0.0194\ x\ 4.174\ x\ (120 - 30.5)}$$

$T_{ho} = 70.5^O C$

2) Temperature of Cold water leaving the Heat Exchanger (°C): $Q_h = M_h\, C_p(T_{hi} - T_{ho})$…………… (ii)

Q_h = Heat transfer rate of the hot steam (W)

Q_h = 0.0194 x 4.174 x (120 – 30.5)

= 4.0083 KJ/hr

= 4008.3W

Rate of heat loss = Rate of heat gain

$Q_c = M_c\, C_p(T_{co} - T_{ci})$ ………………….. (iii)

Q_c = Heat transfer rate of the cold water (W)

T_{co} = Temperature of the cold water leaving the heat exchanger (°C)

4.0083 = 0.0263 x 4.174 x $(T_{co} - 30.5)$

$T_{co} = 67^O C$

3) Coefficient of Heat Transfer at Inner Tube (W/m^2 °C):

$$\Delta T = \frac{T_{in} - T_{out}}{ln\left(\frac{T_{in}}{T_{out}}\right)} \text{………………… (iv)}$$

ΔT = Log. Mean Temperature Difference (°C)

$T_{in} = T_{hi} - T_{ci} = 89.5^O$

$T_{out} = T_{ho} - T_{co} = 3.5^O$

$$\Delta T = \frac{89.5 - 3.5}{ln\left(\frac{89.5}{3.5}\right)}$$

$\Delta T = 26.53\ ^O C$

$A_i = \pi d_i l$………………….. (v)

A_i = Area of the inner tube (m^2)

d_i = Diameter of the inner tube (m)

L = Length of the tube (m)

$A_i = \pi\ x\ 0.01\ x\ 1.2$

$A_i = 0.0377 m^2$

$$U_i = \frac{Q_h}{A_i \Delta T} \text{…………………….. (vi)}$$

U_i = Coefficient of heat transfer at the inner tube (W/m^2 °C)

$$U_i = \frac{4.0083}{0.0377\ x\ 26.53}$$

U_i = 4.00765KJ/m^2 °C

= 4007.65W/ m^2 °C

4) Thickness of the Material for the Tube (mm):

$$Q_h = \left[\frac{1}{\frac{1}{U_i} + \frac{t}{k}}\right] A_i \Delta T \text{ ……………… (vii)}$$

t = Thickness of the material for the tube (mm)

k = Thermal conductivity of copper (398W/m °C)

$$4008.3 = \left[\frac{1}{\frac{1}{4007.65} + \frac{t}{398}}\right] x\ 0.0377\ x\ 26.53$$

t = 0.002m

= 2mm

5) Total Coefficient of Heat Transfer in the Heat Exchanger: (W/m^2 °C): $d_o = di + t$………………… (viii)

d_o = Diameter of the outer tube (m)

d_o = 10 + 2

= 12mm

= 0.012m

$A_o = \pi\, d_o\, L$……………………. (ix)

A_o = Total Surface Area of tube (m^2)

d_o = Diameter at outer surface of tube (m)

$A_o = \pi \times 0.012 \times 1.2$

$A_o = 0.0452\ m^2$

$U_o = \frac{Q_c}{A_o \Delta T}$ ……………………. (x)

U_o = Coefficient of heat transfer outside tube ($W/m^{2\,O}C$)

$U_o = \frac{4008.3}{0.0452 \times 26.53}$

$U_o = 3339.7\ W/m^{2\,O}C$

$U = U_o + U_i$

U = Total coefficient of heat transfer in the heat exchanger ($W/m^{2\,O}C$)

$= 4007.65 + 3339.7$

$= 7347.4\ W/m^{2\,O}C$

6) Number of Inner and Outer Tubes Transfer Units:

$NTU_{(i)} = \frac{U_i + A_i}{C_{min}}$ ……………(xi)

$NTU_{(i}$ = Number of transfer unit at the inner tube

$C_{min} = M_h \times C_p$

$= 0.0194 \times 4.174$

$= 0.0809$ Kw

$= 80.9$W

$C_{max} = M_c \times C_p$………………….. (xii)

$= 0.0263 \times 4.174$

= 0.24m

= 240mm

Based on this specification, 5 number of Baffle are incorporated into the Heat Exchanger.

8) Shell Diameters: The diameter of the shell depends on the tube pitch. The tube pitch is the centre-centre distance of

= 0.10977Kw

= 109.77W

$C = \frac{C_{min}}{C_{max}}$…………………….. (xiii)

C = Capacity ratio

$= \frac{80.9}{109.77}$

$= 0.7369$

$NTU_{(I)} = \frac{4007.65 \times 0.0377}{80.9}$

$= 1.866$

$NTU_{(o)} = \frac{U_o + A_o}{C_{min}}$ …………………(xiv)

$NTU_{(o)}$ = Number of transfer unit at the outer tube

$= \frac{3339.7 \times 0.0452}{80.9}$

$= 1.864$

7) Spacing of Baffle: The spacing of the baffle depends on the materials of the tube, inner diameter of the shell or minimum of one fifth of the length of the tube as in [3]. The spacing of the baffles adapted for this equipment is the latter factor.

$B_S = \frac{1}{5} l$………………… (xv)

B_S = Baffle spacing (m)

L = Length of tube (m)

$B_S = \frac{1}{5} \times 1.2$

adjoining tubes and 1.25 times tube outer diameter is recommended by [4].

$T_p = 1.25 \times d_o$………………… (xvi)

T_p = Tube pitch (mm)

$T_p = 1.25 \times 12$

= 15mm

Based on this value, 10 number of tube was adapted.

$D_I = (T_p \times n)$ + Clearance for the baffles…………… (xvii)

D_I = Internal diameter of the shell (m)

n = No of tubes (10 adapted)

Clearance adapted for the baffle is 20mm

$D_I = (15 \times 10) + 20$

= 170mm

= 0.17m

Thickness of about 2mm is assumed for the thickness of the shell material which is galvanized mild steel plate.

$D_O = 170 + 2$

= 172 mm

= 0.172m

Fig 1: A picture of the tube bundle under construction with layout of about angle of 30^o

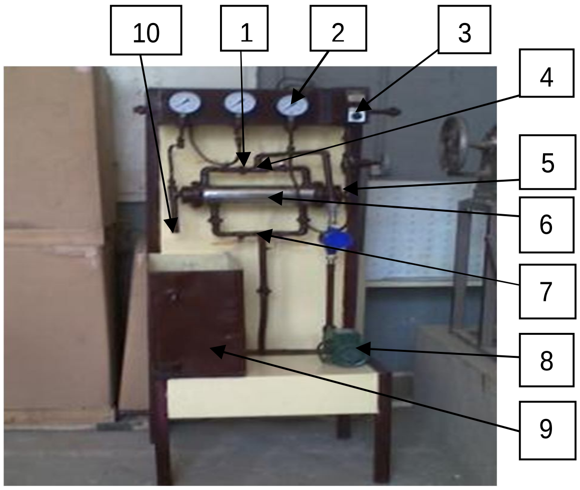

Fig 2: A picture of the small heat exchanger developed to aid the inbuilt cooling system of the overheating 30kva generator

TABLE 1
PART DESCRIPTION

S/n	Part
1	control valve
2	pressure gauge
3	thermocouple
4	hot water inlet
5	hot water outlet
6	heat exchanger
7	cold water inlet
8	cold water outlet
9	pump
10	reservoir

IV. CONCLUSIONS

The equipment was developed and is currently used as auxiliary cooling system of the 30kva generator in the enterprise. Result of performance evaluation showed that the runhours of the generator have increased by about 60%. Prior to installation of this device, the generator shuts down on overheating after working for an average of 50 run hours (dropped working hours due to excessive usage). However this has increased to about 80 runhours before carrying out maintenance activities on the engine.

The prototype Heat Exchanger developed can be adapted to preliminary reduce the temperatures of cooling media especially water from temperature of about 120^{O}C to about 70^{O}C. It can also be used as intermediary means of transferring heat in media which are used to cool machines employed to generate power, processing food, chemical, etc that are subjected to excessive usage due to production demands, poor electricity supply and harsh environmental conditions.

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REFERENCES

[1] J. Coulson and J. Richardson, "Chemical engineering- fluid flow, heat and mass transfer,"*Journal of Reed Educational & Professional Technology*, Vol. 1, pp 1132-1134, 1999.

[2] D. P. Dewitt and F. P. Incropera, *Fundamental of Heat and Mass Transfer*" 3rd ed., NY, USA: Wiley Press, 1990.

[3] E. Dogan, "Thermoeconomic optimization of baffle spacing for shell and tube heat exchangers," *Journal of Energy Conservation and Management*, Vol. 47, pp 1478–1489, 2005

[4] A. J. Hugo, (2008) *Chemical Reaction Modeling; Multiphase Reactive Flow*, 2nd ed., Berlin, Heidelber Germany: Springer Verlag, 2008.

[5] Kakaç and L. Hongtan, *Heat Exchangers; Selection, Rating and Design*" 2nd ed., China: CRC Press, 2002.

[6] J. Kerr. (2011) Auto tech: radiator shutters [Online]. Available: http//www.tandfonline.com/aut-

[7] R. Ladewal and G. Kamaruddin, " Design of small tube and shell heat exchanger," in *Proc. University of Malaysia Institutional Repository of UMP Research and Publication*, 2010, pp. 113

[8] R.K. Rajput, *Heat and Mass Transfer*, 4th ed., New Delhi: S. Chand and Company Ltd, 2000.