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Computational Estimation of Best Heat Exchanger for Power Plant Using MATLAB & COSMOL

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ABSTRACT

The aim of this project is to select appropriate heat exchangers out of available gas-gas heat exchangers for used in a proposed power plant. the heat exchangers are to be used in the power plant for the purposes of waste heat recovery, recuperation and inter cooling.

In selecting an optimum heat exchanger for use, the PCHE was identified as the best candidate for waste heat recovery and recuperation. In order to ascertain the viability of this assertion the PCHE was designed and a 1D modeling performed in MATLAB using the conditions that the heat exchanger for waste heat recovery would be subjected to. The choice of using the conditions that the waste recovery heat exchanger would be subjected to was due to the fact that, it is the heat exchanger that would be subjected to much harsh conditions (thus higher temperatures of up to 650 °C). The PFHE was also designed and similarly a 1D modeling performed in MATLAB. The decision to consider the design of the PFHE was to offer a platform to compare and contrast the performance of the PCHE in order to have a strong basis for deciding on whether to stick to the choice for the PCHE

The results obtained from the 1D modeling of the design of the heat exchangers indicates that the PCHE performed better with regards to pressure drops across the heat exchangers

Results obtained from the simulation of the 3D model buttress the decision to employ the PCHE as heat exchangers to be used for waste heat recovery and recuperation as a wise one

KEYWORDS: *Hear Exchanger, Stimulation, 1D Modeling using MATLAB, 3D modeling using COSMOL, Analysis*

I. INTRODUCTION

The aim of this project is to select appropriate heat exchangers out of available gas-gas heat exchangers for used in a proposed power plant. the heat exchangers are to be used in the power plant for the purposes of waste heat recovery, recuperation and inter cooling.

In selecting an optimum heat exchanger for use, the PCHE was identified as the best candidate for waste heat recovery and recuperation. In order to ascertain the viability of this assertion the PCHE was designed and a 1D modeling performed in MATLAB using the conditions that the heat exchanger for waste heat recovery would be subjected to. The choice of using the conditions that the waste recovery heat exchanger would be subjected to was due to the fact that, it is the heat exchanger that would be subjected to much harsh conditions (thus higher temperatures of up to 650 °C). The PFHE was also designed and similarly a 1D modeling performed in MATLAB. The decision to consider the design of the PFHE was to offer a platform to compare and contrast the performance of the PCHE in order to have a strong basis for deciding on whether to stick to the choice for the PCHE

II. Project Objectives

The aim of this project is therefore to :

- Select an appropriate heat exchanger for used in the Proposed Power Plant after a literature review on available gas-to-gas heat exchangers.
- Build and perform 1D modeling of the selected heat exchanger using MATLAB.
- Last but not the least, perform a 3D modeling of the designed selected heat exchanger using the COMSOL Multi physics software

Heat Exchanger: A heat exchanger is defined as "a device that is used to transfer thermal energy (enthalpy) between two or more fluids, at different temperatures and in thermal contact". Heat exchangers have now become an essential component in most industry processes and this can be traced to the lot of benefits that can be derived from it usage. Heat exchangers are frequently used in refrigeration, heating, air conditioning, power plants, chemical plants, petrochemical plants, waste heat recovery, transportation, manufacturing industries, etc. Various types of heat exchangers are employed for various applications in the sectors mentioned above. Heat exchangers are classify in various ways and notably among them are; according to transfer processes, number of fluids, degree of surface compactness, construction features, flow arrangements and the heat transfer mechanisms.

Classification According to Construction Features:

a. Tubular; the most common type been the shell-and-tube
b. Plate-type (which is also referred to as primary surface recuperators); examples includes Plate, Spiral, Plate coil, Printed circuit and most recently Marbond™ heat exchangers
c. Extended surface; examples are Plate-fin, tube-fin
d. Regenerators; examples are Rotary, Fixed-matrix, and the Rotating hood

It is in this respect that Compact Heat Exchangers (CHEs) have become the preferred choice over the conventional shell and tube heat exchanger, because reduction in size means reduction in weight and cost, since less material would have to be used.

Compact Heat Exchangers

As mentioned earlier, heat exchangers can be classified in various ways one of which is according to the surface compactness (either compact or non-compact). Compact heat exchangers (CHEs) have in recent times become the preferred choice relative to the conventional shell and tube exchangers because of their large heat transfer area per unit volume of the exchanger. Compact heat exchangers are defined subjectively as heat exchangers with surface area densities of equal or greater than $700 m^2/m^3$ for gas-to-fluid heat exchangers and equal or greater than $400 m^2/m^3$ for liquid-liquid and phase-change heat exchangers.

III. Types of Heat Exchangers

There are various types of compact heat exchangers currently in used and some still in its developmental stages, a summary of features of various types of CHEs are

1. Plate and frame heat exchangers
2. Brazed plate heat exchangers
3. Welded plate heat exchangers
4. Plate-fin heat exchangers
5. Printed circuit heat exchangers
6. The Marbond™ heat exchanger

Selection of Heat Exchangers

The decision to select a particular heat exchanger for a specific application can be arrived at by taking into consideration a lot of astute factors since it goes a long way to help realized the rationale for which it is intended. In view of this, much experience and work goes into the selection process. Factors that need to be considered in the selection of heat exchangers for specific applications include;

- High/low pressure limits (pressure limits)
- Thermal performance also known as the effectiveness of the heat exchanger
- Expected working temperature range
- Product mix to be used in the exchanger (liquid-to-liquid, gas-to-gas, etc)

- Pressure drop desired across the expected heat exchanger
- The expected fluid flow capacities over both sides of the heat exchanger
- Method of cleaning employed, maintenance and repairs issues associated with heat exchanger.
- Materials required for construction
- The possibility of future expansion of exchanger when it becomes necessary.
- Last but not the least consideration is, the cost of the heat exchanger

Conclusion for the Selection of a Suitable Heat Exchanger for used as Waste Heat Recovery/ Recuperator

A review of various heat exchangers for high temperature, high effective and low pressure drop applications identify three promising heat exchangers for high temperature applications. These are the Plate-Fin, Printed-circuit and the Marbond™ heat exchangers. The features of the Marbond™ heat exchangers as listed in Table 3-1, makes it attractive for high temperature applications like the proposed power plants and even higher temperature applications, but since it is a new heat exchanger much research and work need to be carried out if it is to be considered for use in the proposed power plant or for other similar applications. The PFHE has been in used for quite some time now, but with its high capital cost and other limitations mentioned earlier does not make it the best option for this application, nevertheless it can be considered as an alternative. The PCHE which has been deem promising is no doubt the exchanger that should be considered for this project, considering its compactness of up to 5000m²/m³, effectiveness as much as 98.7%, and maximum operating of up to 1000°C and pressure up to 500 bars. A summary of the various important attributes of the three shortlist heat exchanger are shown in figure 3-3 attest to the fact that the PCHE is the best option for this application.

IV. Assumptions Made in the Design of the Heat Exchangers

A lot of assumptions are made for the exchanger heat transfer problem formulations (notably in the area of energy balances, rate equations, boundary conditions, and other useful analysis to be considered). An assumption is usually invoked in the design process whenever it becomes necessary. Those that are useful in almost all heat exchanger designs and this application in particular are;

1. The heat exchanger would operate under steady-state condition, i.e. operate with constant flow rates and fluid temperatures (both at the inlet and within the heat exchanger) independent of time.
2. Heat losses to and from the surroundings are neglected.
3. Non existence of thermal energy sources or sinks in the heat exchanger.
4. Uniform distribution of fluid temperature over every cross section of the exchanger.
5. The wall thermal resistance is assumed as a constant and uniform in entire heat exchanger.
6. No phase change, since we are only dealing with flue gases on one side and air on the other side of the exchanger.
7. The individual and the overall heat transfer coefficients of both fluids are assumed constant (thus independent of temperature, time and position) throughout its flow in the heat exchanger matrix.
8. Both fluids employed in the heat exchanger are assumed to be of constant specific heat capacities.
9. The flow velocity and temperature of both fluids at the inlet of the heat exchanger on each fluid side is considered uniform over the flow cross section.
10. The fluid flow rate is uniformly distributed through the exchanger on each fluid side in each pass.

V. Pressure Drop Analysis on the PFHE

The relative pressure drop across the heat exchanger for both fluid sides can be determined from the relation;

$$\left(\frac{\Delta P}{P_{in}}\right) = \frac{G^2}{2P_{in}\,\rho_{in}}\left[(1-\sigma^2+K_c) + f\frac{L\rho_i}{r\rho_o} + 2\left(\frac{\rho_i}{\rho_o}-1\right) - (1-\sigma^2-K_e)\frac{\rho_i}{\rho_o}\right] \quad (38)$$

Where the f used in equation (36) is a corrected f value of the one determined in equation (26), and is determined from the relation;

$$f = [f_0(\frac{T_w}{T_m})^m] \quad (39)$$

With the assumption that there is no fouling, and only thermal resistance on both sides of the exchanger, *Tw* is determine from the relation;

$$T_w = \frac{(T_h/R_h)+(T_c/R_c)}{(1/R_h)+(1/R_c)} = \frac{(\eta_o hA)_h\, T_h + (\eta_o hA)_c\, T_c}{(\eta_o hA)_h + (\eta_o hA)_c} \quad (40)$$

Where; $$R_h = \frac{1}{(\eta_o hA)_h}, \quad (41)$$

$$R_c = \frac{1}{(\eta_o hA)_c} \quad (42)$$

The value of m is determined from tables depending on the type of fluid, the Reynolds number, and state of fluids been employed (either gases or liquids).

Kc and *Ke* are the entrance and exit pressure loss coefficient respectively, which are determined from charts and are dependent on the Reynolds number, surface geometry and the frontal area ratio, σ, which is defined as;

$$\sigma = \frac{b\beta D_h}{4(2b + 2\delta_w)} \quad (43)$$

In equation (43), it is assumed that plate spacing for both fluid sides are the same. The hydraulic radius for the cold and hot side of the heat exchanger is calculated from;

$$r_c = (D_{hc}/4)\,, \qquad r_h = (D_{hh}/4) \quad (44)\text{-}(45)$$

Pressure Drop Analysis of the PCHE

The frictional pressure drop across the exchanger is worth considering, since we seek to find a lower pressure drop heat exchanger. The frictional pressure drop over the PCHE is calculated from;

$$\Delta P_{frict} = f\frac{4L}{D_h}\frac{1}{2}\rho V^2 \quad (57)$$

f is determined for conditions where 0.5 and reynolds number less than 2000

$$f = \frac{64}{Re} \quad (58)$$

However for situations where Re is greater than 2000 the fanning friction is defined as

$$f = (0.79 * (\log(Re) - 1.64))^{-2} \quad (59)$$

VI. Analysis Performed in the PFHE

Selection of appropriate dimensions for the PCHE and the PFHE was arrived at after the sensitivity analysis was performed and table 4.2 and 4.3 below shows the parameters and results from the 1D modeling of the PCHE and PFHE respectively.

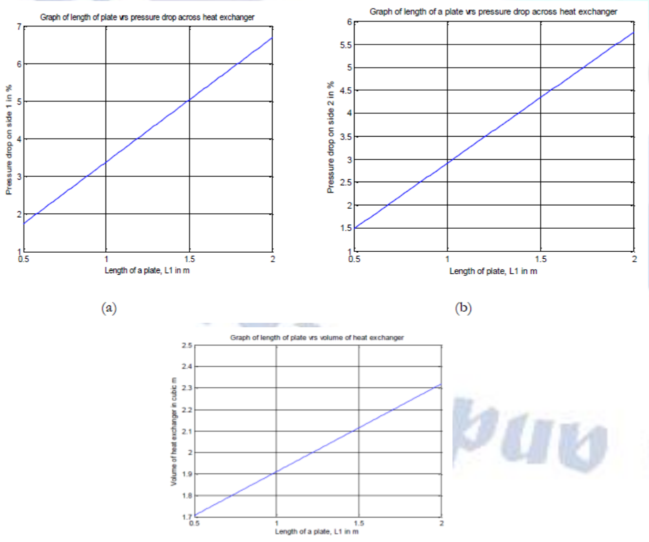

Figure 4-11 (a)-(c); (a) A graph of length of a plate versus pressure drop across side 1 (b) A graph of length of a plate versus pressure drop across side 2 (c) A graph of length of a plate versus the volume of heat exchanger

Table 4.2 Parameters and results of the 1D of the PCHE.

Parameter	Value
Length of exchanger, L (m)	1.1
Diameter of channels, D (mm)	2
Plate thickness, th (mm)	1.5
Total number of plates, N_tCH(-)	1373760
Pressure drop-side 1, (%)	1.17
Pressure drop-side 2, (%)	3.29
Total heat transfer area, A_tot (m²)	5095
Heat transfer coefficient-side 1, (W/m².K)	174
Heat transfer coefficient-side 2, (W/m².K)	201
Overall heat transfer coefficient, U ((W/m².K))	92
Thermal Power, Q (MW)	12.15

Table 4.3 Parameter and results from the 1D modeling of the PFHE

PARAMETER	DIMENSION
Plate thickness, δw (mm)	1.5
Fin thickness, δ (mm)	0.15
Spacing between surfaces of a fin, s (mm)	0.0015
Fin offset length, ℓs (mm)	6
Length of a plate, L1(m)	2.0
Width of a plate, L2(m)	1.6
Flow length in the L1 direction, Lf(m)	L1-0.025
Plate spacing for fluid side 1, b1(mm)	5.545
Plate spacing for fluid side 2, b2(mm)	5.545
Hydraulic diameter, Dh (mm)	3.8
Total number of nf fins (-)	81000
Number of passages, Np	133
Total surface area, A (m2)	4554
Pressure drop on the primary side, ΔP (%)	4.59
Pressure drop on the secondary side, ΔP (%)	4.84

Heat transfer coefficient-Primary side,h_c (W/m2.K)	163.90
Heat transfer coefficient-secondary side, h_h (W/m2.K)	378.48
Overall heat transfer coefficient, U (W/m2.K)	104.91

VII. COMSOL MULTIPHYSICS

The COMSOL Multi physics is also described as an Engineering simulation software that offers an environment which facilitates all steps involved in modeling processes, that is defining the geometry, meshing, specifying the physics to be studied, solving the problem and allows the results to be visualized.

The mathematical formulation used and solved for in COMSOL Multiphysics for **Conjugate Heat Transfer** (also used for almost all simulations in the heat transfer interface) for steady-state, laminar flow interface is the incompressible (is also applicable to compressible flows) Navier-Stokes equations and an energy conservation equation. The Navier-Stokes formulation basically consists of a momentum and continuity equation. The Navier-Stokes equations and the energy conservation equation are derived from the principle of conservation of mass, momentum and energy.

1.Momentum equation

It can be shown by resolution of forces acting on a particle of a cube of fluid that;

$$\rho \frac{Dv}{Dt} = \nabla.\sigma + f$$

Here is the stress tensor and f represents the sum of the various gravitational forces acting on the cube. The stress tensor is however a rank two symmetric tensor which is expressed mathematically by its covariant components consisting of normal stresses, and shear stresses, τ

$$\sigma_{ij} = \begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix}$$

as;

The stress tensor above can further be divided into two distinct terms as;

$$\sigma_{ij} = \begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix} = -\begin{pmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{pmatrix} + \begin{pmatrix} \sigma_{xx}+p & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy}+p & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz}+p \end{pmatrix}$$

And it can also be expressed as;

$$-\begin{pmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{pmatrix} + \begin{pmatrix} \sigma_{xx}+p & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy}+p & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz}+p \end{pmatrix} = -pI + \text{Ŧ}$$

The pressure, p is given by negative of the mean of the normal stresses, i.e.

$$p = -\frac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz}), \mathrm{I}$$

is the 3*3 identity matrix, and Ŧ is the deviatoric stress tensor.

The Navier-Stokes equation can at this point be expressed in its general form as;

$$\rho \frac{Dv}{Dt} = -\nabla p + \nabla.\text{Ŧ} + f$$

And the deviatoric stress tensor, Ŧ can be

$$\text{Ŧ} = \mu(\nabla v + (\nabla v)^T) - \frac{2}{3}\mu(\nabla.v)$$

expressed as;

The Momentum equation for the fluid flow can therefore be simply for steady state analysis as;

$$\rho(v.\nabla)v = \nabla.\left[-p\mathrm{I} + \mu(\nabla v + (\nabla v)^T) - \frac{2}{3}\mu(\nabla.v)\mathrm{I}\right] + F$$

Steps involved in the use of COMSOL Multiphysics:

As mentioned earlier COMSOL Multi physics facilitates all steps involved in modeling, from definining the geometry to meshing.

The tasks involved in the use of COMSOL Multi physics to model the heat exchanger are as enumerated in the following steps;

1. Selecting space dimension to be used for modeling after starting COMSOL Multiphysics (either 1D, 2D or 3D space.
2. Adding physics to the model to be studied
3. Selecting the study type to be undertaken
4. Defining the geometry of component or part to be modeled
5. Adding of materials to be used for the various parts of the model
6. Entering the necessary boundary conditions for the model
7. Meshing, computing and postprocessing

VIII. SIMULATION OF THE MODEL

The 3D model simulated consists of a cube of metal which has four semi-circular (two for the cold fluid and two for the hot fluid) channels running through the length of the block, figure 5-8 Shows a diagram of the 3D model with the semi-circular channels. The model consists of three materials, thus material for the heat exchanger matrix and the two different fluids flowing on both sides (hot and cold) of the exchanger. The material for heat exchanger matrix and air used as fluid for the cold side of the exchanger were selected and added from the built in library materials. The third material (flue gases) was added by entering the necessary properties that would be needed in the simulations since it was not found in the built in materials or material library.

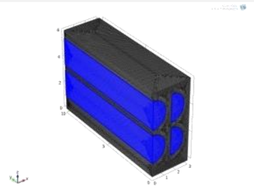

Figure 5-8: A diagram of the 3D model simulated

Selection of meshes and specifying its sizes is the final step before a model is simulated in COMSOL Multiphysics. It is worth noting that choosing of meshes for a model has much influence on the accuracy of results to be obtained from the simulation process. In this regards various meshes were tried for the simulation of the model. Some of these meshes employed resulted in the simulations running for hours without converging to find a solution. The combination of meshes that return some good results after simulation is the case of combining quadrilateral for domains of the geometry and triangular used for the boundaries.

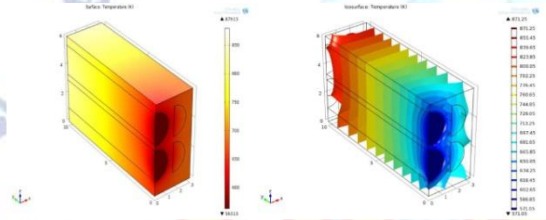

Figure 5-9: Diagrams of the model showing the temperature variations after simulations

After simulations, the model was visualized after which important output parameters calculated for. Figure 5-9 shows the variations of temperature along the length of the model.

IX. Results & Discussion

The results obtained from the MATLAB model for the PCHE is presented in table 6-1, while that for the PFHE is presented in table 6-2. A comparison of some results obtained from the PCHE MATLAB model to that of its 3D model simulated using the COMSOL Multi physics software is also tabulated in table 6-3.

Table 6-1 PCHE Design parameter and results

Parameter	Value
Length of exchanger, L (m)	1.1
Diameter of channels, D (mm)	2
Plate thickness, th (mm)	1.5
Total number of plates, N_tCH(-)	1373760
Pressure drop-side 1, (%)	1.17
Pressure drop-side 2, (%)	3.29
Total heat transfer area, A_tot (m^2)	5095
Heat transfer coefficient-side 1, ($W/m^2.K$)	174
Heat transfer coefficient-side 2, ($W/m^2.K$)	201
Overall heat transfer coefficient, U (($W/m^2.K$))	92
Thermal Power, Q (MW)	12.15

The parameters and some results obtained from the designed of the PCHE using MATLAB are as tabulated in table 6-1. The pressure drops across the side 1 and 2 was determined to be 1.17 % and 3.29 % respectively, heat transfer coefficients for sides 1 and 2 too was also determined to be 174 $W/m^2.K$ and 201 $W/m^2.K$ respectively with an overall heat transfer coefficient of 92 $W/m^2.K$. The thermal power output is as expected across the exchanger, a value which was determined earlier in the proposed power plant.

Table 6-2 PFHE Design parameters and results

PARAMETER	DIMENSION
Plate thickness, δw (mm)	1.5
Fin thickness, δ (mm)	0.15
Spacing between surfaces of a fin, s (mm)	0.0015
Fin offset length, ℓs (mm)	6
Length of a plate, L1(m)	2.0
Width of a plate, L2(m)	1.6
Flow length in the L1 direction, Lf(m)	L1-0.025
Plate spacing for fluid side 1, b1(mm)	5.545
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Hydraulic diameter, Dh (mm)	3.8
Total number of fins nf (-)	81000
Number of passages, Np	133
Total surface area, A (m^2)	4554
Pressure drop on the primary side, ΔP (%)	4.59
Pressure drop on the secondary side, ΔP (%)	4.84
Heat transfer coefficient-Primary side,h_c ($W/m^2.K$)	163.90
Heat transfer coefficient-secondary side, h_h ($W/m^2.K$)	378.48
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Table 6-3 A comparison of results for the PCHE MATLAB model and the 3D model

Parameter	MATLAB model	3D model
Inlet temperature-cold side (K)	563.2	563.2
Outlet temperature-cold side (K)	878.8	858.75
Inlet temperature-hot side (K)	879.2	879.2
Outlet temperature-hot side (K)	602.60	591.37
Heat transfer coefficient-cold side ($W/m^2.K$)	174	205.19
Heat transfer coefficient-hot side ($W/m^2.K$)	201	220.93
Overall heat transfer coefficient ($W/m^2.K$)	92	106
Pressure drop-side 1 (%)	1.17	1.06
Pressure drop-side 2 (%)	3.29	2.47
Effectiveness	90.49	93.59
Thermal Power (MW)	12.15	12.23

A comparison of results obtained from the designed PCHE using MATLAB and that of the 3D model simulated are as tabulated in table 6-3. The inlet temperatures of both sides of the exchanger are the same for both the MATLAB and 3D models since they are initials conditions imposed but the outlet temperatures for the 3D model recorded is slightly lower than that of the MATLAB model. However, there is an improvement in the heat transfer coefficients obtained in the 3D model with values of 205.19 $W/m^2.K$ and 220.93 $W/m^2.K$ as against 174 $W/m^2.K$ and 201 $W/m^2.K$ for the MATLAB model for sides 1 and 2 respectively, with an overall heat transfer coefficients of 92 $W/m^2.K$ for the MATLAB as against 106 $W/m^2.K$ for the 3D model. Pressure drops recorded for the 3D model also showed a slight decrease for the side 1 and a significant decrease for side 2 of the exchanger.

X. Conclusion & Future Scope

The results obtained from the simulations of the 3D model compared to the MATLAB model of the PCHE gave a clear indication that it is a good heat exchanger that can be used to meet the desired requirements of a heat exchanger to be employed in the proposed power plant. The performance of the PCHE I would say looks more promising compared to the PFHE, this can be seen from the results obtained from both the MATLAB and 3D model of the PCHE. The PFHE however, did not perform badly with some good values recorded for the heat transfer coefficients and subsequently a higher overall heat transfer coefficient.

The heat exchanger to be employed in the proposed power plant is to be of higher effectiveness, has a lower pressure drop across and also be compact as possible so as to get benefits that are associated with the use of compact heat exchangers. The performance of the PCHE models with respect to the desired characteristics of the expected heat exchanger was good.

The choice of using the PCHE as the exchanger for the proposed power plant is therefore a wise one and this has been affirmed by the results obtained from both the MATLAB model and 3D models, however I would like to add that considering the results of the PFHE, it can be taken as alternative heat exchanger to the PCHE.

I would like to end this report by making two recommendations for future work or consideration.

1. The pressures of operations for the proposed power plants are very low and that has much effect on the performance of the entire power plant most especially that of the heat exchanger. My first suggestion is therefore that the working pressures of the proposed power plant be increased not forgetting that increasing the working operations pressures should be guided by the type of materials that are been employed. Increasing the working pressures of operations of the power plant has much benefits notwithstanding also the fact that there may be some associated drawbacks. An increased in working pressures of operations in the power plants means an increased in pressures of operations in the heat exchanger, and increasing pressures in the heat exchanger (keeping all other parameters constant) would mean an increased in the density of fluids employed in the exchanger and subsequently decreased in fluid flow velocity. This would mean an increased in Reynolds number and subsequently heat transfer

coefficients while keeping the pressure drop at the minimum, since the heat transfer coefficient varies directly as the Reynolds number and the pressure drops varies directly as the square of the flow velocity.

2. Secondly, I recommend that a different fluid should be tried and tested for used in the proposed power plant most especially in the bottoming cycle since its operations depends heavily on the quantum of waste heat recovered from the topping

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