Transitory Analysis of Heat Exchanger Networks in the Crude Distillation Unit of Port-Harcourt Refinery

Akpa, J. G., Dagde, K. K. And Okoroma, J. U

Department of Chemical/Petrochemical Engineering
Rivers State University of Science and Technology, Port-Harcourt, Rivers State, Nigeria

Corresponding Author: Akpa, J. G

Abstract
Mathematical models that can be used to predict the transient behavior of heat exchangers in a Heat exchanger Network (HEN) have been developed. This analysis is aimed at predicting thermal transients in Heat Exchanger Networks due to temperature fluctuations of inlet streams. This model is used to predict thermal transient of the heat exchanger networks in the crude distillation unit of the New Port-Harcourt refinery. The response of heat exchangers in the entire network to transient input (sinusoidal change in inlet temperature of the cold stream) was investigated. A finite difference numerical scheme is used to develop a solution algorithm for solving the set of partial differential model equations. The results reveals the effect of inlet temperature change on the process streams and possible points where temperature control is required in the heat exchanger networks of the New Port Harcourt refinery.

Keywords: heat exchanger network, transient analysis, Port-Harcourt, Refinery

INTRODUCTION
Heat exchanger network (HEN) is used in process industries where energy recovery systems are required, large amounts of thermal energy are transferred for heating or cooling (Guha and Chaudhuri, 2007) and where the thermal outlet streams condition must be controlled without reducing heat integration to ensure maximum heat integration through minimum utility consumption (Aguilera and Marchetti, 1998); typical examples include crude oil preheating, ethylene plants, exothermic and endothermic reactions and many others. Heat exchangers operate under varying conditions. In actual processes, operating conditions such as inlet temperatures and mass flow rates of the heat exchanging streams do not remain constant but vary continuously with time. Hence gross thermal gradient is set in the process and target temperatures become time variant.

The efficient and appropriate use of heat exchangers under such varying and changing conditions and overcoming unwanted temperature fluctuations at the stream outlets due to changing operating conditions requires the development of adequate models that can predict thermal dynamics and give Time-temperature history at different points of the network. Such models can be used to identify streams and locations requiring installation of temperature controllers and provide the necessary information and tool for the design of efficient control strategy of the network. There are two general approaches to modeling the dynamics of a heat exchanger – distributed and lumped models. Varshney and Panigrahi (2005), Ansari and Mortazavi (2006) and Peng and Ling (2009) all presented distributed heat exchanger models, Roetzel and Xuan (1998), dynamics of multipass heat exchangers; Lou and Roetzel, (2000), plate fin heat exchanger transients; Lou, (2003) one dimensional flow in multi-stream heat exchangers. Works on the lumped cell-based models have been presented by (Mathisen et al., 1994; Varga et al., 1995). Notable advances in the field of dynamic simulation of heat exchangers have also been made by Corres and Marchetti, (1987), Luo et al., (2003) and Konukman and Akman (2005). Most of these models are quite complex and their solutions analytical and tedious. There are three major types of transient inputs (Brunce and Kandlikar, 1995): 1) step input – a sudden change in inlet temperature or flow rate to a new constant value. 2) Frequency input – a periodically varying change in inlet temperature or flow rate, 3) impulse input – a change in inlet temperature or flow rate of infinite amplitude but infinitesimal duration.

Works on the transient response of heat exchangers to step temperature change in inlet temperature or mass flow rate abound (Spiga and Spiga, 1992; Ansari and Mortazavi, 2006). However there are none on transient response to frequency or impulse temperature change.

In this work a simple but effective model for Heat Exchanger Network configuration with the appropriate numerical scheme for computation of
thermal dynamics and response due to frequency type inlet temperature fluctuations is presented. The effectiveness of model is tested with the heat exchanger networks in the crude distillation unit of the Port-Harcourt refining company.

MODEL DEVELOPMENT

Assumptions

The following assumptions are considered in the formulation of the model equations.

Both hot and cold fluids are in plug flow having constant average thermo-physical properties, there is no heat loss to the surroundings due to perfect insulation of the system’s wall, Capacitance and resistance of heat exchanging walls separating the fluids are negligible, the heat transfer coefficient is independent of position and time, fluid is approximately incompressible so that: \( \overline{C_p} \approx \overline{C_V} \), kinetic, potential energy and work terms are neglected; the mass flow rates of both streams do not vary with time and the fouling resistances are negligible.

Mathematical Model for the Heat Exchanger Network

Applying the principle of conservation of energy (energy balance) over an incremental control volume (within which temperature does not vary) around the hot and cold fluids yields the following differential equations after simplification for counter flow heat exchanger:

For the hot fluid:

\[
\frac{\partial T_h}{\partial x} + \frac{V_h}{A_h} \frac{\partial T_h}{\partial t} = - \frac{U_s}{\rho A_h C_p} (T_h - T_c)
\]

For the cold fluid:

\[
\frac{\partial T_c}{\partial x} + \frac{V_c}{A_c} \frac{\partial T_c}{\partial t} = - \frac{U_s}{\rho A_c C_p} (T_h - T_c)
\]

Where:

- \( V \) = average velocity of fluid, \( m/s \)
- \( \rho \) = density of fluid, \( kg/m^3 \)
- \( A \) = heat transfer area, \( m^2 \)
- \( C_p \) = heat capacity of stream, \( KJ/kg.K \)
- \( T \) = Fluid temperature, \( K \)
- \( K \) = Overall heat transfer coefficient, \( W/m^2.K \)
- \( t \) = time, \( s \)
- \( x \) = fluid direction, \( m \)

In order to completely define the problem, initial and boundary conditions are required.

For these model equations, the initial conditions for hot and cold fluids are:

At \( t = 0 \), \( 0 < x < L \)

\( T_h = T_{h0}(x) \), \( T_c = T_{c0}(x) \)

The boundary conditions for hot and cold fluids include:

At \( t > 0 \), \( x = 0 \)

\( T_h = T_{h1}(t) \), \( T_c = T_{c2}(t) \)

At \( t > 0 \), \( x = L \)

\( T_h = T_{h0}(t) \), \( T_c = T_{c0}(t) \)

NUMERICAL SCHEME: Finite Difference Formulation

A finite difference, fully implicit numerical scheme is employed to solve the model equations. To implement this, the length of each heat exchanger in the entire network is divided into \( N \) number of one-dimensional cells as shown below.

Figure 1: Schematic of cell arrangement for hot and cold streams

Using Figure 1, the forward finite-divided difference for the cell centre \( \left( \frac{x}{s} + \frac{1}{2} \right) \) and cell boundary \( \left( \frac{x}{s} + 1 \right) \) variables can be written as:

\[
\frac{\partial T}{\partial x} = \frac{T_{i+1}^{n+1} - T_i^{n+1}}{\Delta x}
\]

The cell centre variables at node \( \left( \frac{x}{s} + \frac{1}{2} \right) \) in equations (3) above are approximated by averaging the neighboring nodes variables as follows:

\[
T_i^{n+1} = \frac{T_{i+1}^{n+1} + T_i^{n+1}}{2}
\]

and

\[
T_i^{n+1} = \frac{T_{i+1}^{n+1} + T_i^{n+1}}{2}
\]

Introducing the subscripts \( h \) for hot and \( c \) for cold into equations (3) and substituting into equations (1) and (2), the finite difference formulations of the model equations are:

(For hot and cold fluid or stream):

\[
\frac{\partial^2 T}{\partial x^2} + \frac{V}{A} \frac{\partial T}{\partial t} = - \frac{U_s}{\rho A C_p} (T_h - T_c)
\]

Substituting equations (4) and (5) into (6) and (7) yields the following equations for the thermal transients for hot stream:

\[
\frac{d}{dt}\left[ T_{h1}(t) + T_{h2}(t) \right] + \frac{V}{A} \left[ T_{h1}(t) + T_{h2}(t) \right] = - \frac{U_s}{\rho A C_p} (T_{h1}(t) - T_{h2}(t))
\]

Simplifying and rearranging yields:
Let

\[
\begin{align*}
\alpha_1 &= 0.5 + \frac{V F_{a,c}}{A T} + \frac{V F_{a,c}}{C P_{a,c} A T_{a,c}} = 0.5 \left( 1 + \frac{V F_{a,c}}{C P_{a,c} A T_{a,c}} \right) + \frac{V F_{a,c}}{A T} \\
\beta_1 &= 0.5 - \frac{V F_{a,c}}{A T} + \frac{V F_{a,c}}{C P_{a,c} A T_{a,c}} = 0.5 \left( 1 + \frac{V F_{a,c}}{C P_{a,c} A T_{a,c}} \right) - \frac{V F_{a,c}}{A T} \\
c_1 &= -\frac{V F_{a,c}}{A T} 
\end{align*}
\]  

(12)

Using equations (10), (11) and (12), equation (9) can be written for hot and cold streams as:

\[
\begin{align*}
\alpha_1 T_{H}^{n+1} + \beta_1 T_{C}^{n+1} + c_1 T_{n}^{n+1} + \beta_1 T_{C}^{n+1} &= 0.5 \left( T_{H}^{n} + T_{C}^{n} \right) \\
\alpha_2 T_{H}^{n+1} + \beta_2 T_{C}^{n+1} + c_2 T_{n}^{n+1} + \beta_2 T_{C}^{n+1} &= 0.5 \left( T_{H}^{n} + T_{C}^{n} \right)
\end{align*}
\]  

(13)

(14)

For a single heat exchanger, a set of simultaneous equation for the hot and cold streams can be written for all nodes \((1 \leq t \leq \text{n node})\) using equations (13) and (14). In these equations the hot fluid inlet temperature \(T_{H}^{n}\) and cold fluid inlet temperature \(T_{C}^{n}\), for counter current flow are known boundary conditions. Therefore, equation (13) and (14) each contains \((\text{n node}-1)\) number of unknowns. A matrix representation of these equations written in the form: \([A][T]=[B]\), where \([A]\) is the coefficient matrix, \([T]\) is the temperature matrix, and \([B]\) is the constant matrix is:

\[
\begin{bmatrix}
\alpha_1 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\
0 & \alpha_2 & 0 & \cdots & 0 & 0 & \cdots & 0 \\
0 & 0 & \alpha_3 & \cdots & 0 & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & \alpha_{n-1} & 0 & \cdots & 0 \\
0 & 0 & 0 & \cdots & 0 & \alpha_n & \cdots & 0 \\
0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\
\end{bmatrix}
\begin{bmatrix}
T_{H}^{n+1} \\
T_{C}^{n+1} \\
T_{n}^{n+1} \\
\vdots \\
T_{H}^{n+1} \\
T_{C}^{n+1} \\
T_{n}^{n+1} \\
\end{bmatrix}
= \begin{bmatrix}
-0.5 T_{H}^{n} \\
-0.5 T_{C}^{n} \\
0 \\
\vdots \\
-0.5 T_{H}^{n} \\
-0.5 T_{C}^{n} \\
0 \\
\end{bmatrix}
\]

Figure 2: Matrix of finite difference representation of model equations

**MATERIALS AND METHODS**

**Process Description of the Crude Distillation Unit (CDU)**

Raw crude oil after setting and dewatering at the tank farm is pumped through a heat exchanger train, the desalter (where salt and sediments are removed), the pre-flash column (for removal of lighter ends), the crude heater where it is heated up and finally to the fractionating column (CDU) where the column the components of the crude are separated according to their boiling points ranges as products.

**Configurations of the Heat Exchangers and Streams**

The entire Heat Exchanger Network in the crude distillation unit was split into three sub Heat Exchanger Networks (HEN’s); Heat Exchanger Network 1 (HEN-1) links the raw crude storage tank to the desalter; Heat Exchanger Network 2 (HEN-2) links the desalter to the preflash column and Heat Exchanger Network 3 (HEN-3) links the preflash column to the heater. The configurations of the three networks showing the heat exchangers, the hot and cold streams and entry and exit temperatures/nodes are shown in Figs. 1, 2 and 3.

![Figure 3: Heat exchanger Network 1 (HEN-1)](image)

![Figure 4: Heat exchanger Network 2 (HEN-2)](image)
The crude is passed through each heat exchanger network to raise its temperature before it enters the distillation column. Therefore the crude will be taken as the cold stream, while the streams from other sections of the refinery used in heating the crude are taken as the hot stream. The inlet temperature of the crude as it enters each network and the hot stream of all heat exchanger are known. The finite difference algorithm is applied to the heat exchangers in a given network. For a single heat exchanger, a set of simultaneous equations were obtained from literature sources as shown in Table 3.

### Table 3: Thermo-physical properties and process parameters for the networks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HEN-1</th>
<th>HEN-2</th>
<th>HEN-3</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_s (m^2)$</td>
<td>31.4</td>
<td>31.4</td>
<td>31.4</td>
<td>PHRC (2005)</td>
</tr>
<tr>
<td>$U (W/m^2.C)$</td>
<td>653.0045</td>
<td>653.0045</td>
<td>653.0045</td>
<td>Bird (2005)</td>
</tr>
<tr>
<td>$S (m^2)$</td>
<td>37.7</td>
<td>37.7</td>
<td>37.7</td>
<td>PHRC (2005)</td>
</tr>
<tr>
<td>$C_p (KJ/kg.C)$</td>
<td>2.7325</td>
<td>2.8169</td>
<td>2.8750</td>
<td>Calculated</td>
</tr>
<tr>
<td>$\rho_s (kg/m^3)$</td>
<td>864</td>
<td>874.5</td>
<td>892.5</td>
<td>PHRC (2005)</td>
</tr>
<tr>
<td>$V_s (m/s)$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>Coulson and Richardson (2005)</td>
</tr>
<tr>
<td>$A_{ph}$</td>
<td>25/25 = 1.0</td>
<td>36/36 = 1.0</td>
<td>18/18 = 1.0</td>
<td>Calculated</td>
</tr>
<tr>
<td>$A_t$</td>
<td>100/25 = 4.0</td>
<td>144/36 = 4.0</td>
<td>72/18 = 4.0</td>
<td>Calculated</td>
</tr>
<tr>
<td>$t (s)$</td>
<td>100 (25^4)</td>
<td>144 (36^4)</td>
<td>72 (18^4)</td>
<td>Calculated</td>
</tr>
<tr>
<td>$A$</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### INLET TEMPERATURE VARIATION

The inlet temperature in each network is time-dependent and follows a temperature variation according to a sinusoidal forcing function given by:

$$ T_i^2 = T_{inlet}^2 + A \sin(t) \quad (17) $$

### RESULTS AND DISCUSSION

#### Effect of Change in Inlet Temperature

For each heat exchanger in a given network, there are four streams (nodes), two inlets (hot – from other sections and cold – crude from source (for first heat exchanger) or from one heat exchanger to another in the network) and two outlets streams (crude been heated and stream used to heat). Therefore not all streams (nodes) are affected by inlet temperature disturbance or fluctuations. All inlet streams from
other sections used for heating are not affected. The transient behavior of outlet streams (hot and cold) of the heat exchangers in a given network to sinusoidal change in temperature of the inlet stream of first heat exchanger in the network was investigated. These behaviors are presented as deviations from operational steady state values of the affected heat exchangers.

Investigation of thermal transient was performed by disturbing inlet feed stream temperatures of HEN-1, HEN-2 and HEN-3 following a hypothetical temperature change or variation of the form: 

\[ T = A \sin(\omega t) \]

for a time step of 1.0s. As the heat exchangers and streams in the networks are thermally integrated, any disturbance in inlet temperature would affect the temperature of other streams. The results of the thermal transients of the outlet streams (nodes) of heat exchangers in HEN-1, HEN-2 and HEN-3 are hereby presented.

The temperature-time profiles of only streams/nodes affected by changes in inlet temperature are presented. In each network there are a number of streams/nodes with close temperature values and identical (streams/nodes that have same temperature), for such streams, the thermal transient of either is presented. The temperature-time profiles of selected streams (1,2,3,4,5,6,7,10,12,16), (1,2,3,4,5,6,7,10,12,16) and (1,2,3,4,5) in Heat exchanger Network 1, 2 and 3 to sinusoidal change of the network’s inlet temperature are presented in Figures 6 and 7, 8 and 9, 10 and 11.
As the temperature of the first node (inlet stream) into each network changes or fluctuates, the outlet temperature of the streams (cold and hot) from the heat exchangers in each network oscillates as shown in Figures 6, 7 for HEN 1, Figures 8 and 9 for HEN 2 and Figures 10 and 11 for HEN 3. These figures show sinusoidal oscillations of the outlet temperatures as deviations from the original steady state values. These oscillatory effects of inlet temperature on the outlet streams are damped out slowly the farther the outlet streams are from the point at which the disturbance was initiated (inlet stream).

From these figures, nodes 2 and 3 shows the most variation in temperature with time since they are closest to the point at which the disturbance is initiated; likewise, all other nodes show similar variations in temperature but with diminishing amplitude as the heat exchanger is located farther from the point of disturbance (node 1).

CONCLUSIONS

A study of the thermal dynamics in HENs of the CDU in the Port-Harcourt refinery has been performed. The impact of sinusoidal wave temperature disturbance applied to inlet conditions (cold stream temperatures) of the HENs on all outlet streams of heat exchangers in the network was investigated.

Results showed that all three heat exchanger networks (HEN’s) are susceptible to inlet stream disturbances; HEN-1 showed more susceptibility to disturbance at nodes closer to the inlet nodes. Similarly, HEN-2 showed extreme susceptibility to disturbance at nodes closer to the inlet nodes, and as such, adequate temperature control strategy should be implemented at inlet of the crude from the desalter. For HEN-3, the nodes closer to the inlet node (where disturbance was introduced) were not extremely affected as they showed only small deviation from steady state values. Results also give an insight of the dynamics of the heat exchanger networks and shows possible heat exchangers that are susceptible/prone to fluctuations. Such information can be useful in the design of adequate and appropriate control strategy for the networks. The implementation of an appropriate control strategy at the inlet of the crude from storage will ensure that desired temperature levels are maintained at the different nodes (streams) in each network.

NOMENCLATURE

\[ C_p \] - Specific heat capacity of the stream (kJ/°C.kg)

\[ d \] - Specific gravity at 15 °C (dimensionless)

\[ F \] - Mass flow rate of the stream (kg/s)

\[ T \] - Temperature (°C)

\[ V \] - Average velocity of fluid (m/s)

\[ \rho \] - Density of fluid (kg/m³)

\[ A \] - Flow area of stream (or heat transfer area) (m²)

\[ U \] - Overall heat transfer coefficient (W/m².K)

\[ t \] - Time (s)

\[ x \] - Fluid direction

\[ S \] - Heat transfer perimeter (m)

Subscripts:

\[ h \] - Hot stream or fluid;

\[ c \] - Cold stream or fluid

\[ i, n \] - Node

REFERENCES


Peng, H. and Ling, X. 2009, Neutral networks analysis of thermal characteristics on plate-fin heat exchanger with limited experimental data, Applied Thermal Engrg. 29 (11-12) 2251-2256


