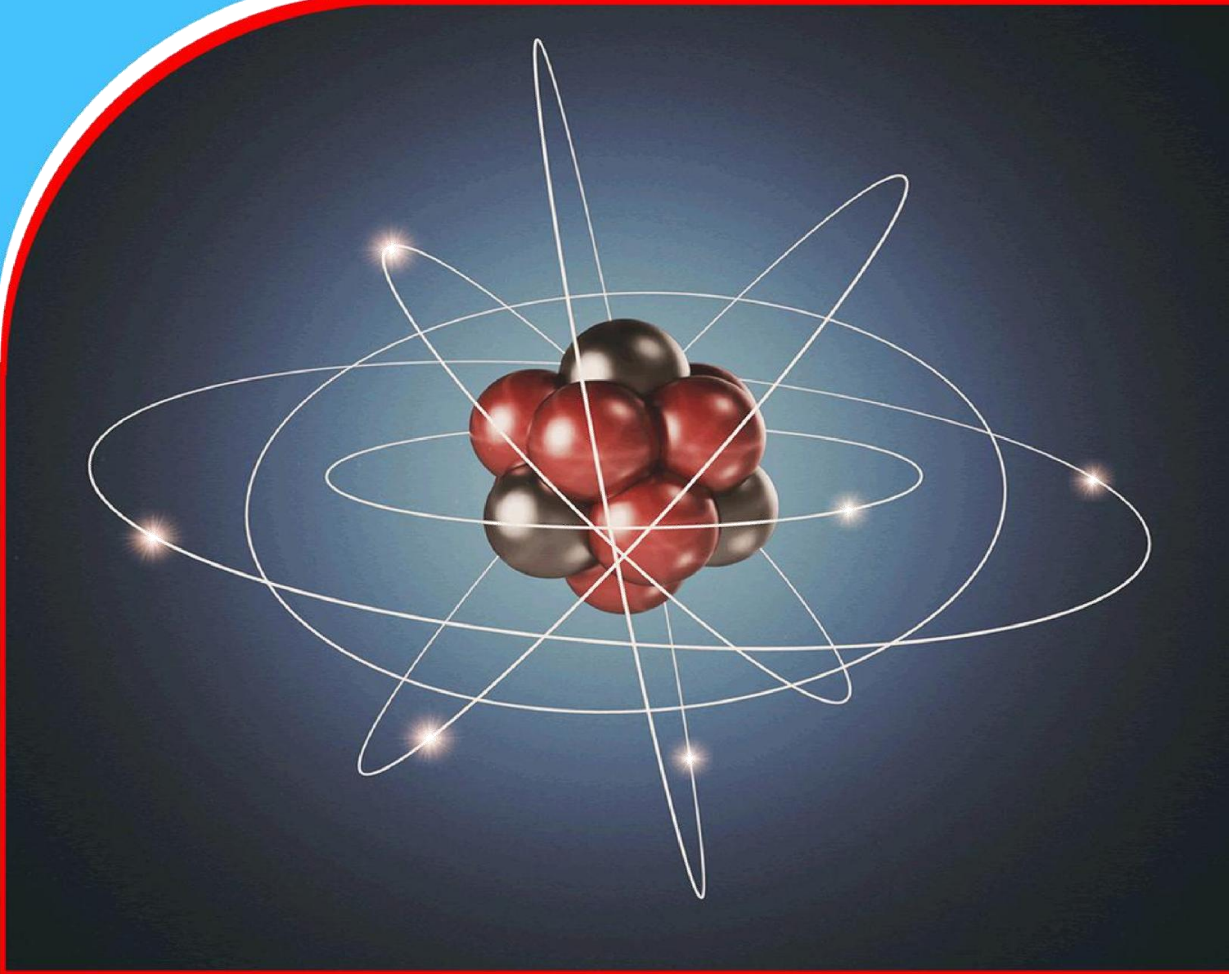
European Journal of
Physical Sciences
(EJPS)



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European Journal of physical Sciences
ISSN 2788-8223 (Online)
Vol.4, Issue 1, pp 49-62, 2021
www.ajpojournals.org

DESIGN ADAPTATION OF BATCH CRUDE OIL BOILER FOR CONTINUOUS DISTILLATION OPERATIONS.

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Abstract

Purpose: Boilers are some of the most critical equipment in many production process especially in refinery operations, as it is used in generating steam for different applications. Different types of boilers are available commercially and have comparative advantages over one another. The pot or kettle boiler is the foremost of these equipment and consists of an empty vessel with a secure lid and a burner that is the source of heating. Though overtaken in industrial applications by more modern designs, these simple boilers which are often batch process equipment are still useful for small production processes at low pressures. The work here developed design adaptation of these batch boilers for continuous vaporization of crude oil for artesian refining of the oil.

Methodology: Physical and assay data of Bonnylight Crude Oil (BLCO) was used for the work from the library of ASPEN Technologies. Simple mathematical models were developed from interpretation of implicit phenomena of the boiler transformation process. The models were validated using ASPEN HYSYS process simulation software Version 10.

Findings: Computational results of the models and simulation results gave good convergence except for the heat transfer parameter of the model which had almost 100% of the simulation value. Nevertheless, the models have good predictive capabilities

Recommendation: The design adaption models herein developed can be deployed with reasonable accuracy for the heating of crude oil especially for small artesian operations. However, the study space of the subject matter can be expanded for better accuracy and reliability.

Keywords: *Design adaptation, Batch, Boiler, Distillation*

1.1 Introduction

Boilers which are generally closed vessels enable the vaporization of its containing fluid (usually water) for the generation of steam for different domestic and industrial applications. Steam is used for water heating, cooking, power generation and even sterilization. Boilers are some of the most fundamental equipment in a process plant or industry. They are frequently used in agro – industry, petrochemical plant, petroleum refining, chemical processing etc (Rayaprolu, 2009). Early boilers were used for steam turbines in locomotives (Bell, 1952) and power generation amongst many other important industrial applications.

Different types of boilers include fire – tube and water – tube boilers, flued boilers, pot or haycock boilers also called kettle boilers (www.wikipedia.com). While tube boilers are the contemporary equipment used for various industrial processes, the pot boilers which were the earliest common boilers are simple to design and construct. As technology of crude oil refining shifts from the traditional giant and complex plants to small modularized systems, application of simple kettle boilers for vaporization of crude oil in the refining process gives a veritable alternative (Igbagara et al., 2018).

The present work explores the possibility of adapting simple kettle boilers (which are traditionally batch process equipment) for continuous refining of crude oil. Relevance of the study lies in the increasing supply gap of petroleum products especially in developing and low income countries. This situation has led to the desperate resort by national governments and individuals alike to simplified low costing refining alternatives. Extensive study of these simple boilers to improve performance for crude oil refining is therefore an expedient endeavour.

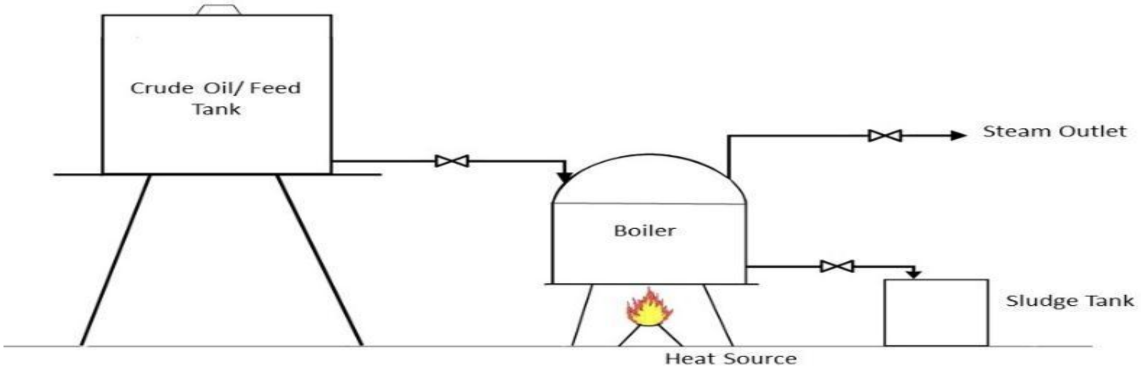

Figure 1: Schematic Diagram of Batch Boiler

1.2 Theoretical Basis of Design

Pot boilers are batch process equipment which operates on a non-steady state basis (Biello, 2008). However, they can be adapted for continuous operation by;

I. Constant introduction of fresh feed as well as withdrawal of product (steam and sludge in this case) during the process and
II. Ensuring that feed introduction and product withdrawal does not significantly change the thermodynamic equilibrium of the process (i.e. to maintain steady temperature and vapour pressure in still).

The second condition of the process requires that steady state stability determination of the process is carried out with respect to process parameters such as temperature and pressure (Kapila, and Poore, 1982). To develop mathematical equations for the process, the following assumptions are made:

i. The process operates in steady state.
ii. Vapour and liquid phases are always in equilibrium during process
iii. There is no mixing of fluid elements in liquid during process (i.e. liquid elements maintain plug flow) with heavy sludge at bottom and lighter fraction at the upper part of still.
iv. There is no sensible heat loss (i.e. still is effectively lagged to prevent heat loss).

1.3. Objectives of the Work

Aim of the present work was to design a simple kettle boiler (a traditional batch boiler) to vaporize crude oil on continuous basis for artesian refining. Reasons for the work are the obvious merits of continuous over batch processes in industrial operations (Kister, 1990). Specific objectives of the work were:

i. To develop model equations that effectively describe the process of converting a batch pot or boiler for continuous operation
ii. Determine the physical dimensions of boiler such as surface area, diameter, height etc
iii. Determine thermodynamic parameters such as molar compositions, boiler vapour pressure and temperature and boiler heat duty.
iv. Determine steady state stability criteria for the continuous crude oil vaporization process
v. Evaluate performance of the boiler by appropriate methods.

2. Mathematical Model i. Material Balance Equation

The overall material balance of the unit is given by;

$$F = V + L \tag{1}$$

ii.

Component Balance Equation

$$x_F^i F = y^i V + x_B^i L \tag{2}$$

Thus from (2);

$$y^i = \frac{F}{V} x_{iF} - \frac{L}{V} x_B^i \tag{3}$$

Equation (3) is only valid within the limits;1.$0 \leq \frac{F}{V} \leq 1.493$ after normalization (Clayton, 2018) as in (4);

$$|y^i| = \frac{F}{V}x_{iF} - \frac{L}{V}|x_B^i| \tag{4}$$

iii. Vapour – Liquid Equilibrium Equation

$$\sum_{i=1}^{n} y^i = \sum_{i=1}^{n} K^i x^i \tag{5}$$

iv. Summation Equation

$$\sum_{i=1}^{n} y^i = 1 \tag{6}$$

I. Heat Balance Equation

$$H_F{}^i F + Q = H_V{}^i V + H_L{}^i L \tag{7}$$

Or in terms of fractional compositions;

$$x_F{}^i H_F{}^i = y^i H_V{}^i + x_B{}^i H_L{}^i \tag{8}$$

Substitution of x_F^i from equation (2), in (8) therefore becomes;

$$(y^i + x_B{}^i)H_F{}^i = y^i H_V{}^i + x_B{}^i H_L{}^i \tag{9}$$

And

$$y^i = \left(\frac{H_L^i - H_F^i}{H_F^i - H_V^i}\right)x_B^i - \frac{Q}{(H_F^i - H_V^i)}$$

or

$$y^i = \frac{Q}{(\Delta H_V^i)} + \left(\frac{\Delta H_L^i}{\Delta H_V^i}\right) x_B^i \tag{10}$$

2.1 Boiler Dimensions Equations

The boiler is a cylindrical vessel with an air – tight lid with a duct for venting off vapour generated. The volume of boiler can be considered to be;

$$V_B = F + V \tag{11}$$

Where;

V= Volume of vapour at desired vapour pressure

But vapour pressure of petroleum and its products is frequently determined using the Reid Vapour pressure test (ASTM 323 test). It gives the Reid vapour pressure of a liquid as a ratio of vapour to liquid volume as (Moshfeghian, 2017);

$$RVP = \frac{V}{L} = 4 \tag{12}$$

Substituting (12) in (11) therefore gives the volume of boiler as;

$$V_B = F + 4L \qquad (13)$$

2.2 Boiler Heat Duty Equation

The amount of heat Q, required to raise temperature of the feed in boiler to a temperature of vapour that can be flashed into a distillation column is given by;

$$Q = H_V + H_L \qquad (14)$$

Equation (15) can be written in term of boiler temperature as;

$$Q = (m_V C_{PV} + m_L C_{PL})\Delta T \qquad (15)$$

Also, the quantity of heat transferred across a surface is given by;

$$Q = UA_c\Delta T \qquad (16)$$

Therefore combining (15) and (16) yields the heat transfer area as;

$$A_c = \frac{m_V C_{PV} + m_L C_{PL}}{U} \qquad (17)$$

2.3 Steady State Stability Equation

From the works of Rosenblat (1977), and Loose and Joseph (1977), the stability of the solution (response curve) for an equation as:

$$F_1(y^i, x_{iB}) = y^i - \frac{F}{V}x_{iF} - \frac{L}{V}x_{iB} = 0 \qquad (18)$$

is given by the sign of the exponent (sometimes called stability exponent) □, given by:

$$\sigma = F_{yi}(y^i, x_{iB}) \qquad (19)$$

When□□0, the solution and hence steady state is unstable. But when□□ 0, the solution is stable. Thus an exchange of stability takes place at the point□□0.

Similarly, to determine stability of the set of simultaneous equations presented below, use is made of the analysis of Poore (1973), which gives the point of bifurcation to periodic orbits (oscillatory state) also called Hopf bifurcation points along the steady state response curve as roots of the trace of the Jacobian matrix given in (20) as:

$$Trace\ J(y^i, x_{iB}) = 0 \qquad (20)$$

$$F_1(y^i, x_{iB}) = y^i - \frac{F}{V}x_{iF} - \frac{L}{V}x_{iB} = 0 \tag{21}$$

$$F_2(y^i, x_{iB}) = y^i - \frac{Q}{(\Delta H_V^i)} + \left(\frac{\Delta H_L^i}{\Delta H_V^i}\right)x_B^i = 0 \tag{22}$$

The Jacobian matrice of (22) and (23) can be written as:

$$J = \frac{\partial(F_1, F_2)}{\partial(y^i, x_{iB})} = \begin{vmatrix} \frac{\partial F_1(y^i, x_{iB})}{\partial y^i} & \frac{\partial F_1(y^i, x_{iB})}{\partial x_{iB}} \\ \frac{\partial F_2(y^i, x_{iB})}{\partial y^i} & \frac{\partial F_2(y^i, x_{iB})}{\partial x_{iB}} \end{vmatrix} \tag{23}$$

And results in (24).

$$J(y^i, x_{iB}) = \begin{vmatrix} 1 & -\frac{L}{V} \\ 1 & \left(\frac{\Delta H_L^i}{\Delta H_V^i}\right) \end{vmatrix} \tag{24}$$

Thus Trace$J(y^i, x_{iB})$ is given by;

$$\text{Trace}\, J(y^i, x_{iB}) = \frac{\Delta H_L^i}{\Delta H_V^i} + 1 = 0 \tag{25}$$

$$\frac{\Delta H_L^i}{\Delta H_V^i} = -1 \tag{26}$$

Also, determinant of the Jacobian matrix is;

$$Det.J(y^i, x_{iB}) = \frac{\Delta H_L^i}{\Delta H_V^i} = -\frac{L}{V} \tag{27}$$

Equations (26) and (27) meet both conditions (19) and (20) for the existence of a stable steady state as values of the stability coefficients are less than zero.

3. Results and Discussion

Bonnylight crude oil assay data from ASPEN Technology library (2011) was used for the numerical computations in this work and are given in Tables 1 and 2. The basis of computation was 100 litres/hour of crude oil throughput and a 90% product recovery.

Table 1: Bonnylight Crude Oil Cut Yields (2011)

Product Cuts	Temp (℃)	% Vol	% Mole	% Mass

Off Gases	IBP – 70	6.32	13.00	4.6
Naphtha	70 – 221.1	29.03	41.67	26.72
Kerosene	221.1 – 371.1	37.00	32.19	38.51
Diesel	371.1 – 537.8	19.50	10.34	21.27
Residue	537.8 – FBP	7.40	2.80	8.83

Numerical computations in the work were based on the assumption that 90% of all products as indicated in Table 1 were recovered from the feed except the residue. From basic principles of distillation design, it is known that only a little fraction of the residue is found in the distillate (Mujtiba, 2004). Consequently, Table 3 gives the adjusted product recovery data based on the assumption above.

Table 2: Physical Properties of Bonnylight Crude Oil

Property	Whole Crude	Vapour	Liquid
Fraction	1.00	0.8361	0.1639
Temp (℃)	25	350	350
Pressure (atm)	1.0	3.0	3.0
Molar Flowrate (kgmol/h)	0.3745	0.3163	0.062
Mass Flowrate (kg/h)	70.52	47.83	22.75
Std Ideal Liq. Vol. flow(l/h)	82.81	58.63	24.24
Liq. Vol. flow @ std cond.(l/h)	1980	1394	586.4
Molar Enthalpy (kj/kgmol)	-4.063e-5	-1.78e-5	-5.038e-5
Heat flow (kj/h)	-1.522e-5	-8.633e-4	-3.124e-4
Molecular Weight	188.3	151.2	367.0
Molar Density (kgmol/m^3)	4.499	0.0622	4.499
Mass Density(kg/m^3)	847.2	9.399	847.2
Act. Vol flow (m^3/h)	0.08324	5.089	0.08324
Molar Volume (m^3/kgmol)	0.2223	16.09	0.2223
Heat Capacity Cp(kj/kgmol-C)	340	408.8	1053
Thermal Conductivity(W/m- K)	0.1169	0.03729	0.1169

Table 3: Percent Vaporization of Components (Adjusted)

Product Cuts	Temp (°C)	Vol. Fraction	Vap. Fraction 90% (y)	Liq. Fraction 10% (x_B)
Off Gases	IBP – 70	0.063	0.0567	0.0063
Naphtha	70 – 221.1	0.290	0.261	0.029
Kerosene	221.1 – 371.1	0.370	0.333	0.037
Diesel	371.1 – 537.8	0.200	0.18	0.02
-	-	-	10%	90%
Residue	537.8 – FBP	0.077	0.0077	0.0693
$\sum_{i=1}^{n} x^i$	-	1.00	0.8384	0.1616

Development of models for adaptation of the batch boiler for continuous operation was based on vapour - liquid equilibrium shown in Figure 2. Vapour composition reduces with increase in composition of the liquid, typical of any vapour – liquid system. However, the design equation defining the equilibrium relationship in this work is only valid within $1.0 \leq |Y| \leq 1.493$. The equilibrium vapour – liquid equation breaks down outside the limit given above. In practical terms, $|Y|$ is given by ratio of the volume of feed (F) to volume of vapour (V) as shown in equation (4). For both Dalton's law of partial pressure, and Raoult's law of mixtures, which are the defining laws for vapour - liquid equilibrium to be obeyed, the summation of molar fractions of individual components in the vapour and liquid phases must be equal to unity. This condition is only met when 1.$0 \leq \frac{F}{V} \leq 1.493$ for the present model.

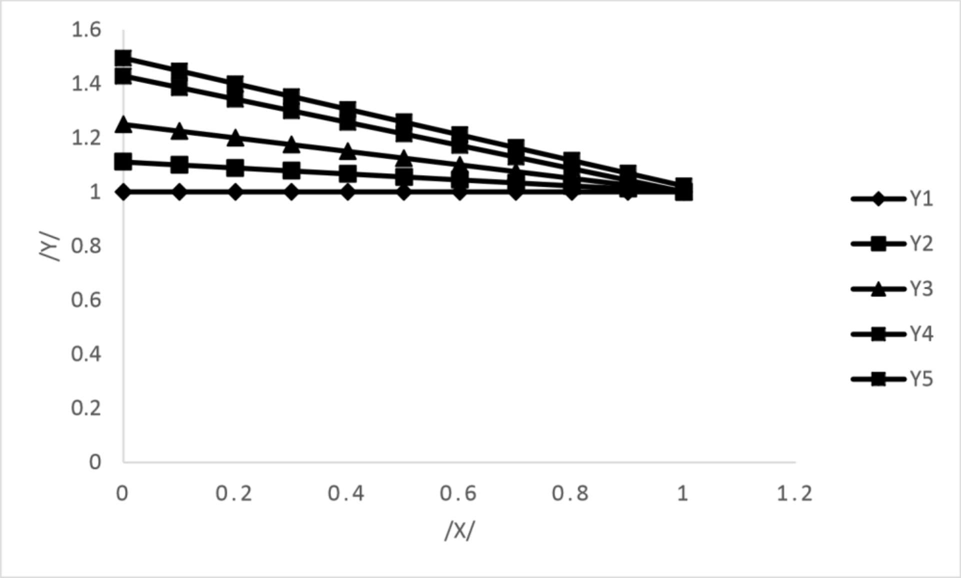

Figure 2: Functional Domain of Model based on Vapour - Liquid Equilibrium

Similarly, limiting conditions of the model shown in Figure 2 for vapour – liquid equilibrium also apply to the heat transfer model shown in Figure 3 (though not conspicously). Only heat duties within the limits of 134393.22 btu/hr and 150,000 btu/hr are valid for the design. The foregoing presupposes an operational mode that has high precision as the functional domain of the design is rather small. It is also important to note that heat duty of the model compares favourably with modern crude oil heaters even though the present design is ultra – simplified.

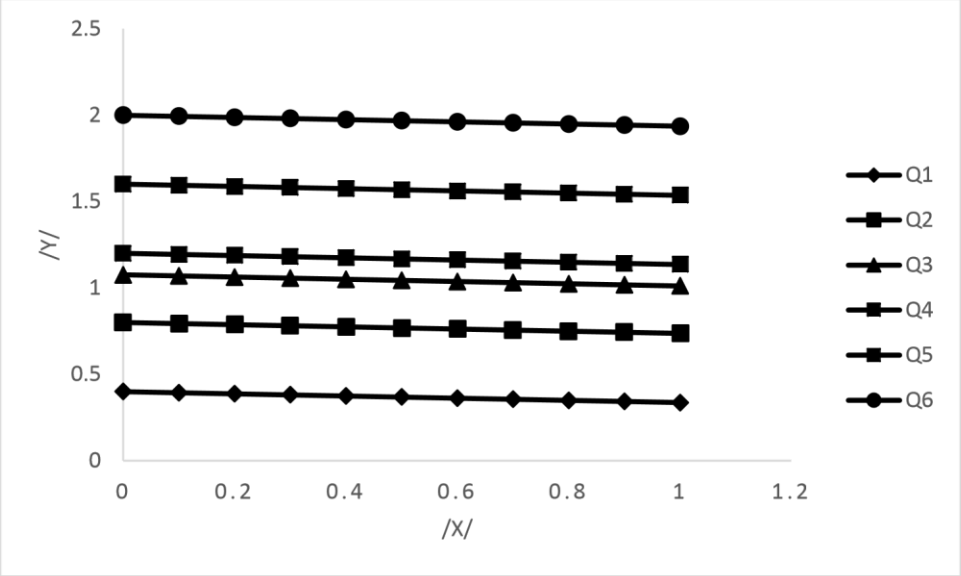

Figure 3: Boiler Heat Duty based on Vapour - Liquid Equilibrium

Figure 4 shows the variation of heat duty (Q) with heat transfer area (Ac) at different thermal conductivities of Carbon Steel used. The profiles reveal consistent increase of heat duty with heat transfer area for different steel conductivities.

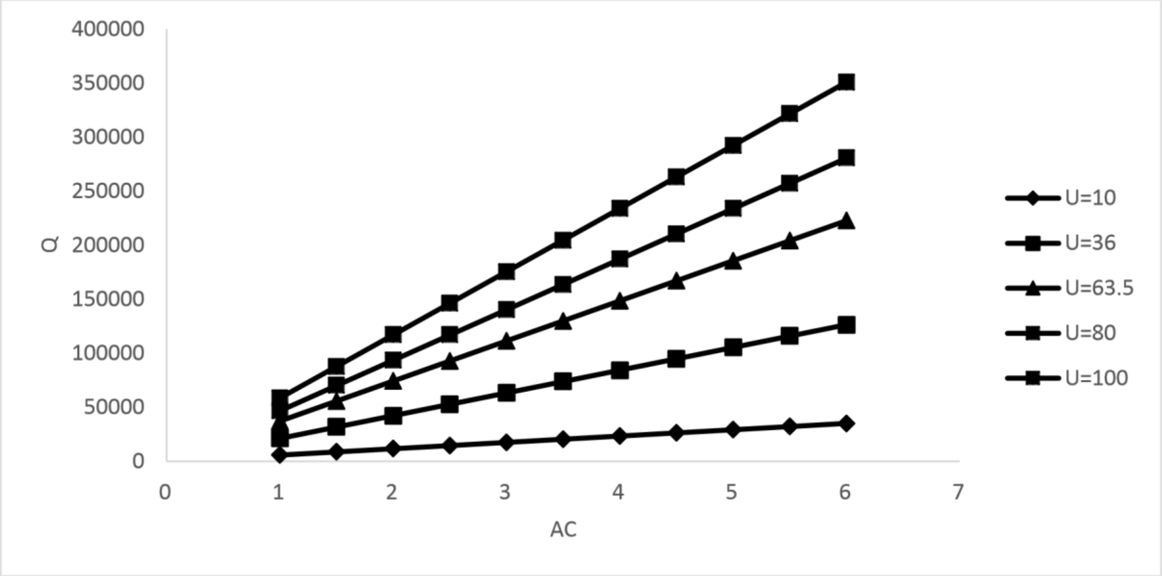

Figure 4: Variation of Boiler Heat Duty with Heat Transfer Area

As thermal conductivity of Carbon Steel increases from (10 – 100) W/mK, heat duty increases rather more severely with area as seen from the steepness of the slopes. The foregoing presupposes that steel materials with higher thermal conductivities are better for construction for optimum design, in line with general principles of heat transfer (Reizes, J.A., 1992).

Another important and interesting outcome of the work is stability of the model represented by profile of enthalpies of the vapour and liquid phases, given in Figure 5. Linearity of the profile shows that there is only a single steady state in the system, commonly described as unique steady state (Loose and Joseph, 1977). Also, given earlier in section 2.3 are the stability criteria for a system of defining equations (Rosenblat, 1977, and Poore, 1973).

Since equations (26) and (27) gave numerical values that are less than one (<1), they meet both conditions (19) and (20) for the existence of a stable steady state. Noteworthy however, is the functional domain of these systems of equations given in earlier sections of the work.

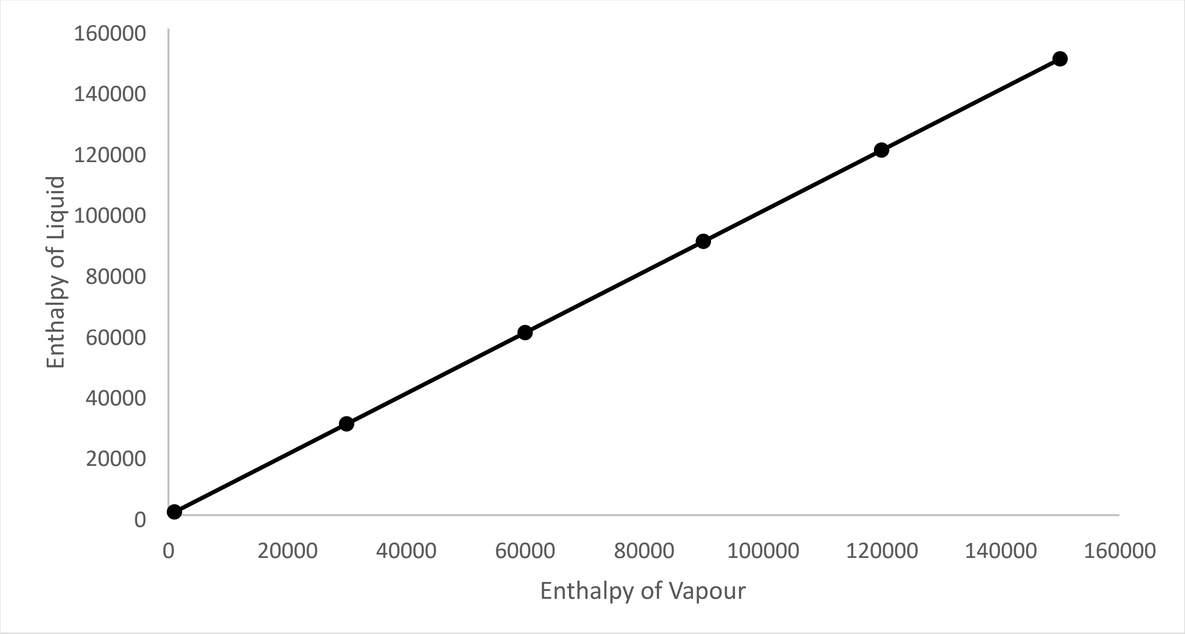

Figure 5: Steady State Stability of the Model based on Enthalpies

Finally, results of computations for boiler dimensions at a temperature of 350°C and vapour pressure of 4 atmospheres are given in Table 4. There is good convergence between computational results and computer simulation using ASPEN HYSYS simulator. The only significant deviation is in the heat transfer parameter with over 50% difference in its nominal value. Nevertheless, computational results are within tolerable limits for such engineering designs (Baredar et al., 2020).

Table 4: Results of Boiler Dimensions for Model Computations and Experiment

Dimensions	$V_B\ (ft^3)$	$H_B\ (ft)$	$D_B(ft)$	**Vap. Vol (bpd)**	**Liq. Vol. (bpd)**	$Q\ (btu/hr)$
Model Computation	5.82	1.6	2.15	10.48	2.02	134,393.22
HYSYS Simulation	5.81	1.6	2.15	10.43	2.15	79, 296.21
Deviations	0.01	0	0	0.05	- 0. 13	55,097.01

4. Conclusion

The design adaptation of a batch pot for continuous crude oil vapourization gave quite feasible physical dimensions with high constructability. This is in addition to the high vapour yield of 90% as against the conventional batch pots with usually low yield (Kister, 1990). The improved product yield is however not unexpected as continuous processes give better yield than their batch counterparts (Kister, 1990). Efficiency of the models in this work is also seen in the consistency of it performance variable with established principles of distillation and crude vaporization.

5. Recommendation

The design is therefore recommended as an alternative to the regular high costing and relatively complex designs currently used for the purpose of crude oil vaporization in distillation or refining. The design adaption models herein developed can be deployed with reasonable accuracy for the heating of crude oil especially for small artesian operations. However, the study space of the subject matter can be expanded for better accuracy and reliability. The unique contribution to knowledge by this work is the ability of the models to reveal and show the narrow parameter regime for conversion and stable operation of the batch boiler as a continuous system.

Notation

$A_c - Heat\ transfer\ area$

$C_{PL} - Specific\ heat\ capacity\ of\ liquid$

$C_{PV} - Specific\ heat\ capacity\ of\ vapour$

$F - Volume\ of\ feed\ (litres)$

$H_F{}^i - Enthalpy\ of\ feed\ (kJ/kmol)$

$H_V{}^i - Enthalpy\ of\ vapour\ (kJ/kmol)$

$H_L{}^i - Enthalpy\ of\ liquid\ (kJ/kmol)$

$J - Jacobian\ matrix$

$K^i - Vapour - liquid\ equilibrium\ constant$

$L - Volume\ of\ liquidin\ (litres)$

$m_L - Mole\ fraction\ of\ liquid$

$m_L - Mole\ fractionof\ vapour$

$Q - Quantity\ of\ Heat\ require\ for\ vapourization\ (kJ/kmol)$

$T - Temperature\ (K)$

$U - Overall\ Heat\ transfer\ coefficient\ (-----)$

$x_B{}^{-i} - Mole\ fraction\ of\ compoment\ i\ left\ in\ still$

$x_F{}^{i} - Mole\ fraction\ of\ compoment\ i\ in\ feed$

$y^i - Mole\ fraction\ of\ compoment\ i\ in\ vapour$

$V - Vapour\ volume\ (litres)$ -

$V_B - Boiler\ volume\ (litres)$

$\sigma - Stability\ coefficient$

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