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Responses application to monitor and predict crude oil distillation rate using pneumatic control system on a furnace

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In this paper, mathematical model were developed to evaluate the different types of responses for monitoring and predicting the furnace output temperature of crude oil at various time intervals. Result obtain reveals increase in furnace output temperature with increase in coefficient of time for different input signal at constant time. Similarly, as the time increases, it is observed that the furnace output temperature increases as well as presented in this research work. At constant coefficient of time, it is observe that the furnace output temperature increases with increase in time for step input, ramp input, and impulse. The order of magnitude in terms output temperature is ramp input > step input > impulse at constant time coefficient of 10 s^{-1}. The model developed was used principally to monitor and control the temperature of the crude oil entering the crude distillation column also to account for the effect of the variations in the finance fuel flow rate and the influence of the changes in the feed temperature and using the model dynamic open loop simulations are performed, and approximation based on parallel linear transfer function models are fitted to various input responses. The result obtained from the model was compared with existing furnace data of Nigerian Liquefied Natural Gas (NLNG) which indicates that step input response was used in the design of their furnace.

Key words: Responses, crude oil, pneumatic control, furnace, application, distillation.

INTRODUCTION

Initially process control was envisioned primarily, as a means of controlling the quality of products in a given process. This vision further gave birth to automatic control, a means of reducing manufacturing cost by cutting down payroll expenses, increasing production and improving product quality (Ogoni and Ukpaka, 2004). Instrumentation in the engineering context deals with the physical construction, details and arrangement of instruments use for monitoring and controlling process streams in industries.

The production of desire product from the plant must meet market quality specification, set by consumers and it is the conscience of the engineers. The specifications may be expressed as chemical composition or physical properties, performance properties or a combination of equipment protection and smooth operation (Jegla, 2006; Busman and Guan, 2001). Process control contributes to good plant operation by maintaining the operating conditions required for excellent product quality. The pneumatic controller has been the predominant type, used in the process industries, during the past few years the electronic controller has found increasing application especially in new plants today. The basic purpose of a pneumatic controller is to supply controlled pressurized air to a pneumatic valve activator in response to an error signal, due to deviation of the measured variable from the

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set point (Xing-Xuan et al., 2004; Mussatic and Juan, 2009; Wei et al., 2002; Abilov et al., 2002).

The furnace burn fuel gas to heat the process liquid (crude oil) flowing through the tube in the fire box. Firing demand is determined by a temperature controller located on the process liquid as it exist the furnace (Cheng et al., 1999). As long as we use control algorithms with an integrating term (PI or PID), the upstream demand signal becomes the set point for both controllers and the desire ratio would be married (Hyun and Ko, 2000). For columns that use a low reflux ratio, feed enthalpy changes can significantly alter the vapor / liquid rates inside the column, causing a major significant upset in the product composition (Jegla et al., 2000; Williams, 1999; Wang et al., 2001).

The basic function of a crude distillation unit is to provide include separation of the crude oil feed mixture into the desired fractions to the further processed to achieve other useful components. A preheating furnace is one of the crude units quality of performance is depending on the functionality of its preheating furnace which in turn determine the performance of the unit's operation of the process (Mir and Zahra, 2011).

The aim of this research is to develop a mathematical model which is set to achieve the following objectives such as: monitor and control the temperature of the crude oil entering the crude distillation column, account for the effect of variation in the furnace fuel flow rate and the influence of changes in the feed temperature and feed flow rate on the furnace effluent temperature monitor and predict the effect of temperature on crude oil distillation, monitor and the effect of combustion rate on furnace output temperature for effective separation mechanism of the products and finally monitor and predict the effect of combustion rate and furnace temperature on the function conversion of the products. The mathematical model developed from the research was simulated using various control response approach which can be attributed to safe, smooth, quality product and profitable output from distillation products. (Ogoni and Ukpaka, 2004, Bussman and Baukal, 2009, Li and Guan, 2001 and Garg, 1999)

MATERIALS AND METHODS

The crude oil fed to the furnace is first preheated in the convection section by heat transfer with the exiting flue gases. From there it flows into the radiation section to be partially vaporized. The fuel (natural gas) is fed to the furnace burners, undergoes combustion whose products (flue gas) exits the furnace through the convection section. Several potential sources of accumulation may contribute to the dynamic response of the furnace: (a) the flue gas, (b) the tubes and the fluids in the convection section, (c) the tube and fluid in the radiation section, (d) the combustion zone gas and (e) the furnace walls.

The dynamics of the furnace are controlled by thermal accumulation in the furnace walls and the dynamic response of the fluid in the radiation section. Thus, our system is described by three dynamic equations, resulting from an energy balance on the furnace walls and from mass and energy balances on the crude flowing in the radiation section.

The model is based on the following assumptions:

(i) The fluid carried through the furnace in the tube is assumed to be homogeneous. The tube walls are assumed to be wetted by this fluid at all times.
(ii) The heat flux into the tubes is assumed to be uniform around the tube circumference. This assumption therefore ignores the fact that part of the tube walls face away from the source of radiation.

This model therefore consists of two principal components:

(a) A description of the heat distribution of the heat of combustion between the crude pipe bearing furnace walls and effluent flue gases. This part of the model will account for thermal accumulation of the furnace walls.
(b) A model describing the flow of crude oil in the radiation section of the furnace, resulting from mass and energy balances.

Mathematical model

In developing the mathematical model for the operating system, a constant volume system through which crude oil flows at a constant mass flow rate, because the incoming crude oil (process fluid) temperature may vary hence provision is made for heating up the crude oil within the furnace. The fuel gas composition is presented in Table 1.

Fuel gas combustion

In the combustion process, the rapid chemical combination of oxygen with the combustible portion of the fuel results in heat release. Combustion of fuel gas produces flue gases. It is vital that the fuel and air thoroughly mix; otherwise complete combustion cannot take place. Perfect combustion occurs when just enough air has been supplied to burn all the fuel. To ensure that all the fuel has been consumed, additional air is supplied. This extra air is called "excess air". A combustion process with high excess air increases the amount of fuel gas. When we reduce this excess air, we reduce the volume of flue gas and the hot gases spend more time in contact with the heat transfer surfaces. This reduces the exit flue gas temperature. So to reduce the mass of the flue gas, we reduce the excess air to the level so as to put the correct amount of combustion air into the process. If we supply too little air, we get incomplete combustion and the formation of carbon monoxide followed by smoke and solid emission. Gaseous fuels require minimum amount of excess air. The fuel gas combustion describing the molecular fraction and the chemical equation of combustion for various components is shown in Table 2.

$$Considering\ Total\ mols\ of\ fuel = n$$

$$0.75nCH_4 + 1.5nO_2 \rightarrow nCO_2 + 2nH_2O \quad (1)$$

$$0.15nC_2H_6 + 0.525nO_2 \rightarrow 0.3nCO_2 + 0.45nH_2O \quad (2)$$

$$0.06nC_3H_8 + 0.30nO_2 \rightarrow 0.18nCO_2 + 0.24nH_2O \quad (3)$$

$$0.04nC_4H_{10} + 0.260nO_2 \rightarrow 0.16nCO_2 + 0.20nH_2O \quad (4)$$

Assuming 10% excess air,

Table 1. Fuel gas composition.

Component	Formula	Mol. weight	Mol. %	Mol. fraction
Methane	CH_4	16.043	75	0.75
Ethane	C_2H_6	30.07	15	0.15
Propane	C_3H_8	44.097	6	0.06
n-Butane	C_4H_{10}	58.124	4	0.04
Total			**100**	**1.00**

Table 2. Fuel gas combustion.

Component	Mol. fraction	Chemical equation of combustion
CH_4	0.75	$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$
C_2H_6	0.15	$C_2H_6 + 3.5O_2 \longrightarrow 2CO_2 + 3H_2O$
C_3H_8	0.06	$C_3H_8 + 5O_2 \longrightarrow 3CO_2 + 4H_2O$
nC_4H_{10}	0.04	$C_4H_{10} + 6.5O_2 \longrightarrow 4CO_2 + 5H_2O$

$$Total\ amount\ of\ O_2\ required = (1.5n + 0.525n + 0.30n + 0.260n)O_2 \quad = 2.585nO_2 \tag{5}$$

$$10\%\ excess\ air = \left(\frac{10}{100} \times 2.585n\right) + 2.585n \tag{6}$$

$$Total\ amount\ of\ O_2 = 2.8435n\ mols\ of\ O_2$$

This implies that; 2.8435 mols of O_2 is required to completely combust 1mol of fuel gas.

Air contains 79% by volume of N_2 and 21% by volume of O_2

$$Air = (O_2 + 3.76N_2) \tag{7}$$

Overall reaction

$$0.75nCH_4 + 0.15nC_2H_6 + 0.06nC_3H_8 + 0.04nC_4H_{10} + 2.8435n(O_2 + 3.76N_2) \rightarrow 1.64nCO_2 + 2.89nH_2O + 0.2585nO_2 + 10.69156nN_2 \tag{8}$$

Distribution of energy of combustion

The energy balance equation for distribution of energy of combustion is given as:

Total Energy Going into the system = Total Energy Going out of System + Total Energy stored within system (9)

But

$$Total\ Energy\ going\ into\ the\ system = Combustion\ Energy + Energy\ in\ Crude \tag{10}$$

$$Combustion\ Energy = H_c^o \tag{11}$$

$$Energy\ in\ Crude = \dot{m}_{oil} Cp_{oil} dT \tag{12}$$

$$Total\ Energy\ going\ into\ the\ system = H_c^o + \dot{m}_{oil} Cp_{oil} dT \tag{13}$$

$$= [(0.75nH_f^o)_{CH_4} + (0.15nH_f^o)_{C_2H_6} + (0.06nH_f^o)_{C_3H_8} + (0.04nH_f^o)_{C_4H_{10}} + (1.64nH_f^o)_{CO_2} + (2.89nH_f^o)_{H_2O}] + \ell_{oil} V_{oil} Cp_{oil} dT \tag{14}$$

Substituting the values of H_f^o of the various components of the gas from thermodynamic $H_f^o\ table$ into Equation 14 gives;

$$= (0.75n \times -74.85) + (0.15n \times -84.67) + (0.06n \times -103.8) + (0.04n \times) + (1.64n \times) + (2.89n \times) + \ell_{oil} V_{oil} Cp_{oil} dT \tag{15}$$

$$Total\ Energy\ going\ out\ of\ the\ system = Flue\ gas\ energy + Q_{Rad}\ to\ pipe \quad (16)$$

$$Flue\ gas\ energy = 1.64n(H^T - H^{25})_{CO_2} + 2.89n(H^T - H^{25})_{H_2O} + 0.2585n(H^T - H^{25})_{O_2} + 10.69156n(H^T - H^{25})_{N_2} \quad (17)$$

Representing in integral form, we have;

$$Flue\ gas\ energy = [1.64n\int_{25}^{T_t} CpdT]_{CO_2} + [2.89n\int_{25}^{T_t} CpdT]_{H_2O} + [0.2585n\int_{25}^{T_t} CpdT]_{O_2} + [10.69156n\int_{25}^{T_t} CpdT]_{N_2} \quad (18)$$

$$Q_{Rad}\ to\ pipe = \sigma(A_{cp})F(T_g^4 - T_t^4) \quad (19)$$

Substituting Equations (18) and (19) into Equation (16) gives:

$$[1.64n\int_{25}^{T} CpdT]_{CO_2} + [2.89n\int_{25}^{T} CpdT]_{H_2O} + [0.2585n\int_{25}^{T} CpdT]_{O_2} + [10.69156n\int_{25}^{T} CpdT]_{N_2} + \sigma(A_{cp})F(T_g^4 - T_t^4) \quad (20)$$

Where Q_{Rad} is the radiant heat transfer rate (W), σ is Stefan-Boltzmann constant (W/m^{2}K^4), α is absorption efficiency factor, A_{cp} is cold plane area of tubes (m^2), F is radiation exchange factor, T_g is temperature of fuel gas (K) and T_t is tube surface temperature (K).

A given body can absorb or emit radiant energy. At thermal equilibrium the ratio of emissive power of a surface to its absorptivity is the same for all bodies. A perfect radiator has an emissivity of one. Such a surface must have an absorptivity of one and reflectivity of zero. This hypothetical surface is commonly referred to as a black body. The ratio of the emissive power of an actual surface to that of a black body is known as emissivity. At thermal equilibrium the emissivity and absorptivity of a body are identical.

A typical emissivity table shows value for the types of surface commonly used in processing.

The surface being studied here is Brick (Red) surface with an emissivity of 0.93. Total amount of energy stored in the furnace is neglected.

Substituting Equations (15) and (20) into (9) we have:

$$(0.75n\times -74.85) + (0.15n\times -84.67) + (0.06n\times -103.8) + (0.04n\times) + (1.64n\times) + (2.89n\times) + \ell_{oil}V_{oil}Cp_{oil}\frac{dT}{dt} = [1.64n\int_{25}^{T} CpdT]_{CO_2} + [2.89n\int_{25}^{T} CpdT]_{H_2O} + [0.2585n\int_{25}^{T} CpdT]_{O_2} + [10.69156n\int_{25}^{T} CpdT]_{N_2} + \sigma(A_{cp})F(T_g^4 - T_t^4) \quad (21)$$

$$\ell_{oil}V_{oil}Cp_{oil}\frac{dT}{dt} = \{ [1.64n\int_{25}^{T} CpdT]_{CO_2} + [2.89n\int_{25}^{T} CpdT]_{H_2O} + [0.2585n\int_{25}^{T} CpdT]_{O_2} + [10.69156n\int_{25}^{T} CpdT]_{N_2} + \sigma(A_{cp})F(T_g^4 - T_t^4) \} - \{(0.75n\times -74.85) + (0.15n\times -84.67) + (0.06n\times -103.8) + (0.04n\times) + (1.64n\times) + (2.89n\times)\} \quad (22)$$

Equation (22) is the mathematical model for the system and can be used to investigate the behavior of the system.

Modeling of the fluid in the radiation section

Energy balance

The mathematical model was formulated by considering the energy balance around the tubes using the necessary conditions and assumptions as presented in this project.

Crude oil is seen to flow in a plug flow condition

$$\text{Rate of Accumulation of Energy} = \text{Rate of input of Energy} - \text{Rate of output of Energy} \quad (23)$$

$$\text{Accumulation} = \frac{dH}{dt} = \frac{d(mh)}{dt} = \frac{d(\ell A\delta zh)}{dt} = \frac{d(\ell A\delta zCpT)}{dt} \quad (24)$$

$$\text{Rate of input Energy} = \dot{m}CpT + \delta Q_{Rad} \quad (25)$$

$$\text{Rate of output Energy} = \dot{m}CpT + \delta Q_{Rad} - (\dot{m}CpT + \frac{\delta(\dot{m}CpT)}{\delta z}dz) \quad 26)$$

Substituting Equations (24), (25) and (26) into (23), we have;

$$\frac{d(\ell A\delta zCpT)}{dt} = \ell FCpT + \delta Q_{Rad} - \left[\ell FCpT + \frac{\partial}{\partial z}(\ell FCpT)dz\right] \quad (27)$$

Cancelling out like terms from RHS of Equation (27) gives;

$$\frac{d(\ell A\delta zCpT)}{dt} = \delta Q_{Rad} - \frac{\partial}{\partial z}(\ell FCpT)dz \quad (28)$$

Assuming ℓ, A, Cp is constant

$$\ell ACp\frac{dT}{dt} = \frac{\delta Q_{Rad}}{\delta z} - \frac{\partial(\ell FCpT)}{\partial z} \quad (29)$$

Since ℓ is constant, F is constant

$$\ell ACp\frac{dT}{dt} = \frac{\delta Q_{Rad}}{\delta z} - \ell FCp\frac{dT}{dz} \quad (30)$$

Dividing both sides of Equation (45) by ℓACp gives Equation (31)

$$\frac{dT}{dt} = \frac{dQ_{Rad}}{dz} \times \frac{1}{\ell ACp} - \frac{dT}{dz} \times \frac{F}{A} \quad (31)$$

For part of the tubular reactor which is situated in the radiant part of the furnace with the process fluid (crude oil) at a temperature lower than the furnace wall, heat transfer occurs mainly by radiation and the rate will be virtually independent of the actual temperature of the reaction mixture. For this part of the reactor, $\frac{dQ_{Rad}}{dz}$ may be virtually constant.

$$A\frac{dT}{dt} + F\frac{dT}{\delta z} = \frac{1}{\ell Cp} \times \frac{dQ_{Rad}}{\delta z} \quad (32)$$

Mass balance inside the tube

Density and velocity can change as the fluid flows along the axial or z direction. There are now 2 independent variables; time 't', and position 'z'. ℓ and V are both functions of both t and z: ℓ(t,z) and V(t,z).

Applying continuity equation:

$$[Mass\ flow\ into\ system] - [Mass flow\ out\ of\ system] = [Time\ rate\ of\ change\ of\ mass\ inside\ system] \quad (33)$$

The differential element is located at an arbitrary spot z down the pipe; it is dz thick and has an area equal to the cross-selection area of the pipe A.

Time rate of change of mass inside system = $\frac{d(A\ell dz)}{dt}$ (34)

Where dz is the volume of the system and ℓ is the density.

Mass flowing into the system through boundary at z is designated as;

$$VA\ell \quad (35)$$

Mass flowing out of the system through boundary at $z + dz$ is given as;

$$VA\ell + \frac{\partial(VA\ell)}{\partial z}dz \quad (36)$$

The above expression for the flow at $z + dz$ may be thought of as a Taylor Series expansion of a function $f(z) around\ z$. The value of the function at a spot dz away from z is:

$$f_{(z+dz)} = f_{(z)} + \left(\frac{\partial f}{\partial z}\right)_{(z)} dz + \left(\frac{\partial^2 f}{\partial z^2}\right)_z \frac{(dz)^2}{2!} + \cdots \quad (37)$$

If the dz is small, the series can be truncated after the first derivative term. Letting $f(z) = VA\ell$ gives equation (36). Substituting these terms into Equation (33) gives;

$$\frac{\partial(A\ell dz)}{\partial t} = VA\ell - \left[VA\ell + \frac{\partial(VA\ell)}{\partial z}dz\right] \quad (38)$$

Cancelling out dz terms and assuming A is constant yields;

$$\frac{\partial \ell}{\partial t} + \frac{\partial(V\ell)}{\partial z} = 0 \quad (39)$$

Liquid densities can be assumed constant in many systems unless large change in composition and temperature occurs.

Control system model

In developing the mathematical model for the operating system we considered a constant volume system through which crude oil flows at a constant mass flow rate, because the incoming crude oil (fluid) temperature may vary hence provision is made for heating up the crude oil (liquid) within the furnace.

With Figure 1 developing a mathematical model for the system by writing the macroscopic energy balance for the constituent parts, therefore for the liquid phase;

$$Accumulation = \ell_L V_L C_L \frac{dT_L}{dt} \quad (40)$$

$$Rate\ of\ energy\ inflow\ fluid = \dot{m}C_L(T_L - T_0) \quad (41)$$

$$Rate\ of\ energy\ inflow\ heat\ transfer\ component\ in\ the\ furnace = U_A(T_{htc} - T) \quad (42)$$

Now applying the conservation law, it is possible to obtain the following;

$$\ell_L V_L C_L \frac{dT_L}{dt} = U_A(T_{htc} - T) + \dot{m}C_L(T_L - T_0) \quad (43)$$

Equation (43) constitutes the mathematical model for the system and can be used in investigating the behavior of the system.

Feedback control

From the model that has been developed, an energy balance at steady state around the heating process may be written as;

$$q_s = U_A(T_{htc} - T) + \dot{m}C_L(T_L - T_0) \quad (44)$$

Where q_s is the heat input to the furnace at steady state design value. Thus T_0 is the normally anticipated inlet temperature of the crude oil to the furnace and for a satisfactory design the steady state value of the output stream T_L must equal T_D (desired output temperature). Hence

$$q_s = UA(T_{htc} - T) + \dot{m}C_L(T_D - T_0) \quad (45)$$

However it is clear from a physical situation that if the furnace is set to deliver only the constant input q_s, then if process conditions

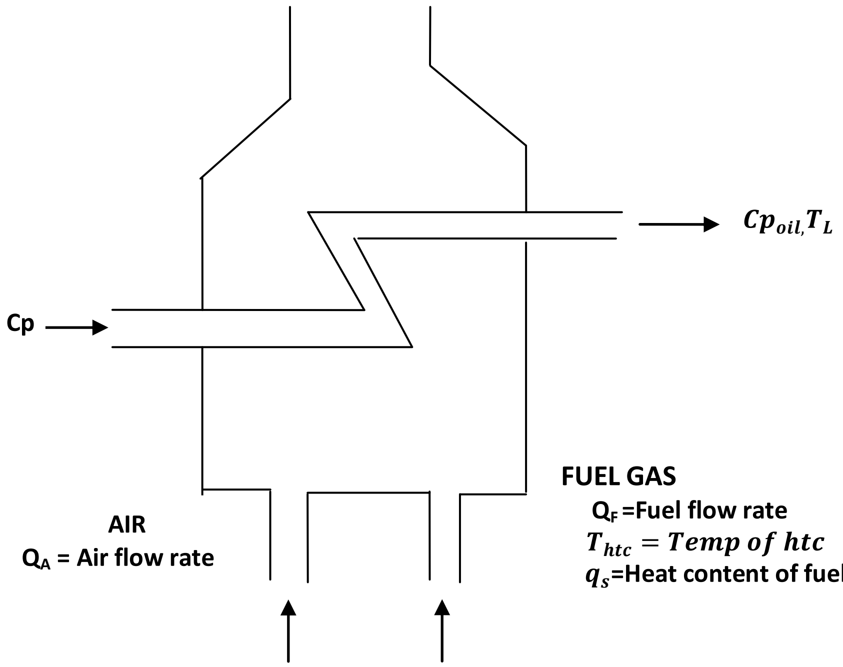


Figure 1. A preheating furnace.

change then the effluent stream temperature will also change from T_D. A typical process condition that may change is the inlet temperature T_0. An obvious solution to the problem is to design the furnace such that its energy input may be varied as to maintain T_L at or near T_D. To be able to make these control decisions, we must be able to know how the effluent stream T_L changes with respect to q and T_0. This necessitates writing the transient energy balance for the process;

$$\ell_L V_L C_L \frac{dT_L}{dt} = U_A(T_{htc} - T) + \dot{m}C_L(T_L - T_0) \quad (46)$$

The controller will use the existing values of T_L and T_D to adjust the heat input according to a predetermined formula. Let the difference between these temperatures $T_D - T_L$ be called the error. Clearly the larger this error the less we are satisfied with the present state of affairs and vice versa. In fact we are only satisfied when the error is exactly zero. Based on these assumptions it is necessary to consider that the controller should change the heat input by an amount proportional to the error. Thus a plausible formula for the controller to follow is;

$$q(t) = UA(T_{htc} - T) + \dot{m}C_L(T_D - T_0) + K_c(T_D - T_0) \quad (47)$$

Where K_c is a positive constant of proportionality called proportional control. In effect the controller is instructed to maintain the heat input at the steady state design value q_s as long as $T_D = T_L$. If T_L deviates from T_D, causing an error; the controller is to use the magnitude of the error to change the heat input proportionally.

The concept of using information about the deviation of the system from its desired state to control the system is called feedback control. Information about the state of the system is fed back to a controller which utilizes this information to change the system in some way. In the present case, the information is the temperature T_0 and the change is made in q. when the term $UA(T_{htc} - T) + \dot{m}C_L(T_D - T_0)$ is abbreviated to q_s, Equation (47) becomes;

$$q = q_s + K_c(T_D - T_0) \quad (48)$$

Transient responses

The mathematical equation defining the transient response in relationship to changes in the functional parameters as presented below.

$$\ell_L V_L C_L \frac{dT_L}{dt} = U_A(T_{htc} - T) + \dot{m}C_L(T_L - T_0) + q_s + K_c(T_D - T_0) \quad (49)$$

$$\ell_L V_L C_L \frac{dT_L}{dt} = U_A T_{htc} - U_A T + \dot{m}C_L T_L - \dot{m}C_L T_0 + q_s + K_c T_D - K_c T_0 \quad (50)$$

$$\ell_L V_L C_L \frac{dT_L}{dt} + K_c T_0 + C_L T_0 = U_A T_{htc} - U_A T + C_L T_L + q_s + K_c T_D \quad (51)$$

$$\frac{\ell_L V_L C_L}{\dot{m}C_L} \frac{dT_L}{dt} + \frac{K_c T_0}{\dot{m}C_L} + \frac{\dot{m}C_L T_0}{\dot{m}C_L} = \frac{U_A T_{htc}}{\dot{m}C_L} - \frac{U_A T}{\dot{m}C_L} + \frac{\dot{m}C_L T_L}{\dot{m}C_L} + \frac{q_s}{\dot{m}C_L} + \frac{K_c T_D}{\dot{m}C_L} \quad (52)$$

$$\tilde{\imath}\frac{dT_L}{dt} + \left(\frac{K_c}{\dot{m}C_L} + 1\right)T_0 = \frac{1}{\tilde{\imath}}\tau(T_{htc} - T) + T_L + \frac{q_s}{\dot{m}C_L} + \frac{K_cT_D}{\dot{m}C_L} \quad (53)$$

Where $\tilde{\imath} = \frac{\ell_L V_L}{\dot{m}} = \frac{1}{\tilde{\imath}}\tau = \frac{U_A}{\dot{m}C_L}$

The term τ has the dimensions of time and is known as the time constant of the furnace. Equation (53) describes the way in which the effluent temperature changes in response to T_0 and q.

$$\tilde{\imath}\frac{dT_L}{dt} - T_L = \frac{1}{\tilde{\imath}\tau}(T_{htc} - T) + \frac{q_s}{\dot{m}C_L} + \frac{K_cT_D}{\dot{m}C_L} - \left(\frac{K_c}{\dot{m}C_L} + 1\right)T_0 \quad (54)$$

Taking initial T_0 value as 1, Equation (54) becomes;

$$\tilde{\imath}\frac{dT_L}{dt} - T_L = \frac{1}{\tilde{\tau}}(T_{htc} - T) + \frac{q_s}{\dot{m}C_L} + \frac{K_cT_D}{\dot{m}C_L} - \left(\frac{K_c}{\dot{m}C_L} + 1\right) \quad (55)$$

Let $\beta = \frac{1}{\tilde{\imath}\tau}(T_{htc} - T) + \frac{q_s}{\dot{m}C_L} + \frac{K_cT_D}{\dot{m}C_L} - \left(\frac{K_c}{\dot{m}C_L} + 1\right)$ (56)

Therefore Equation (55) becomes;

$$\tilde{\imath}\frac{dT_L}{dt} - T_L = \beta \quad (57)$$

Applying Laplace transformation to Equation (57) gives;

$$\frac{dT_L}{dt} = ST_{L(s)} - T_{L(0)} \quad (58)$$

$$T_L = T_{L(s)} \quad (59)$$

$$\beta = \beta \times {}^1/_S \quad (60)$$

In putting Equations (58), (59) and (60) into Equation (57) gives;

$$\tilde{\imath}\left(ST_{L(s)} - T_{L(0)}\right) - T_{L(s)} = \frac{\beta}{S} \quad (61)$$

$If\ T_{L(0)} = 0\ (boundary\ condition)$, Equation (61) becomes;

$$\tilde{\imath}\left(ST_{L(s)}\right) - T_{L(s)} = \frac{\beta}{S} \quad (62)$$

$$T_{L(s)}(\tilde{\imath}S - 1) = \frac{\beta}{S} \quad (63)$$

$$T_{L(s)} = \frac{\beta/_S}{(\tilde{\imath}S - 1)} \quad (64)$$

$$T_{L(s)} = \frac{\beta}{S(\tilde{\imath}S - 1)} \quad (65)$$

Applying the law of partial fraction to resolve Equation (65), we have;

$$T_{L(s)} = \frac{\beta}{S(\tilde{\imath}S - 1)} \equiv \frac{A}{S} + \frac{B}{(\tilde{\imath}S - 1)} \quad (66)$$

$$\frac{\beta}{S(\tilde{\imath}S - 1)} = A(\tilde{\imath}S - 1) + B(S) \quad (67)$$

Let $S = 1$ be the first assumed value, and then substitute into Equation (67) gives;

$$\frac{\beta}{S(\tilde{\imath}S - 1)} = \frac{\{A(\tilde{\imath}S - 1)\} + B(S)}{S(\tilde{\imath}S - 1)} \quad (68)$$

$$\beta = A(1 - 1) + B(1) \quad (69)$$

$$\beta = B \quad (70)$$

Therefore $B = \beta\tilde{\imath}$ (71)

Let $S = 0$ be the next assumed value, and then substitute into Equation (67) gives;

$$\frac{\beta}{S(\tilde{\imath}S - 1)} = \frac{\{A(\tilde{\imath} \times 0) - 1\} + B(0)}{S(\tilde{\imath}S - 1)} \quad (72)$$

$$A = -\beta \quad (73)$$

Substituting the values of A and B into Equation (66), we have;

$$T_{L(s)} = \frac{\beta}{S(\tilde{\imath}S - 1)} \equiv \frac{-\beta}{S} + \frac{\beta\tilde{\imath}}{(\tilde{\imath}S - 1)} \quad (74)$$

Therefore the time inverse of Equation (74) can be expressed as;

$$T_{L(t)} = -\beta + \beta e^{\frac{t}{\tilde{\imath}}} \quad (75)$$

Inputting the value of β as represented in Equation (56) we have;

$$T_L(t) = -\left(\left(\frac{1}{\tau}\right)(T_{htc} - T) + \frac{q_s}{mC_L} + \frac{K_CT_D}{mC_L} - \left(\frac{K_c}{mC_L} + 1\right)\right) + \ell^{\frac{t}{\tau}}\left[\frac{1}{\tau}x\tau(T_{htc} - T) + \frac{q_s\tau}{mC_L} + \frac{K_CT_D\tau}{mC_L} - \left(\frac{K_c}{mC_L} + 1\right)\tau\right] \quad (76)$$

$$T_L(t) = -\frac{1}{\tau}(T_{htc} - T) - \frac{q_s}{mC_L} - \frac{KcT_D}{mC_L} + \left(\frac{Kc}{mC_L} + 1\right) + \ell^{\frac{t}{\tau}}(T_{htc} - T) - \ell^{\frac{t}{\tau}}\frac{q_s\tau}{mC_L} + \frac{K_CT_D\tau}{mC_L}\ell^{\frac{t}{\tau}} - \left(\frac{K_c}{mC_L} + 1\right)\tau\}\ell^{\frac{t}{\tau}} \quad (77)$$

Computational data

Considering a furnace with the following parameters for the combustion zone and the process side;

$$Heat\ Transfer\ Coefficient\ of\ the\ furnace\ wall = UA = 200W/m^2K$$

$$Temperature\ of\ heat\ transfer\ component = T_{htc} = 850K$$

$$Mass\ flow\ rate\ of\ crude\ oil = \dot{m} = 10{,}000kg/h$$

$$Initial\ temperature\ of\ heat\ transfer\ component = T = 800K$$

$$Specific\ Heat\ capacity\ of\ Crude\ oil = C_L = 2.13 \times 10^3 J/KgK$$

$$Desired\ output\ temperature\ of\ crudeoil = T_D = 623K$$

To calculate the constant heat input into the system we apply Equation (45) which states;

$$q_s = UA(T_{htc} - T) + \dot{m}C_L(T_D - T_0)$$

In putting the values, we have;

$$q_s = 200W/m^2K(850K - 800K) + 10{,}000Kg/h \times 2.13 \times 10^3 J/KgK(850K - 800K)$$

$$q_s = 3.834 \times 10^6 KW/m^2h$$

Recall Equation 76 and apply the necessary fundamental parameter to test for the value of $T_{L(t)}$ at different "t" and "τ" value.

$$T_L(t) = -\left(\frac{1}{\tau}(T_{htc} - T)\ \frac{q_s}{mC_L}\ \frac{K_C T_D}{mC_L} - (\frac{K_c}{mC_L}\ 1)\right)\ \ell^{\frac{t}{\tau}}\left[\frac{1}{\tau} x\tau\ (T_{htc} - T)\ \frac{q_s\tau}{mC_L} + \frac{K_C T_D \tau}{mC_L} - \left(\frac{K_c}{mC_L} + 1\right)\tau\right]$$

Application of furnace output temperature to different types of responses

Step input response

These are function that changes instantaneously from one level to another. If the step size is equal to 1, then it is called a unit step function. Considering a first order process control, where

$$T_{L(S)} = \frac{KT_{0(S)}}{\tilde{\iota}s+1} \quad (78)$$

For step response,

$$T_{0(s)} = \frac{A}{s} \quad (79)$$

$$T_{(s)} = \frac{KA/_s}{\tilde{\iota}s+1} \quad (80)$$

$$T_{(t)} = KA(1 - e^{\frac{-t}{\tilde{\iota}\tau}}) \quad (81)$$

Calculating the $T_{(t)}$ value at $\tilde{\imath} = 10, A = T_D = 623K\ and\ t = 20\,s - 28\,s$

Ramp input response

These are functions that changes linearly with time.

$$T_{L(S)} = \frac{KT_{0(S)}}{\tilde{\iota}s-1} \quad (82)$$

For ramp input response,

$$T_{0(s)} = \frac{A}{s^2} \quad (83)$$

$$T_{(s)} = \frac{KA}{s^2(\tilde{\iota}s-1)} \quad (84)$$

$$T_{(t)} = KA\tilde{\imath}\left(\tilde{\imath}e^{\frac{-t}{\tau\tilde{\imath}}} - 1\right) + KA\tilde{\imath} \quad (85)$$

Impulse input response

This is a direct delta function, an infinitely high pulse whose width is zero and area is unity.

$$T_{L(S)} = \frac{KT_{0(S)}}{\tilde{\iota}s-1} \quad (86)$$

For impulse response;

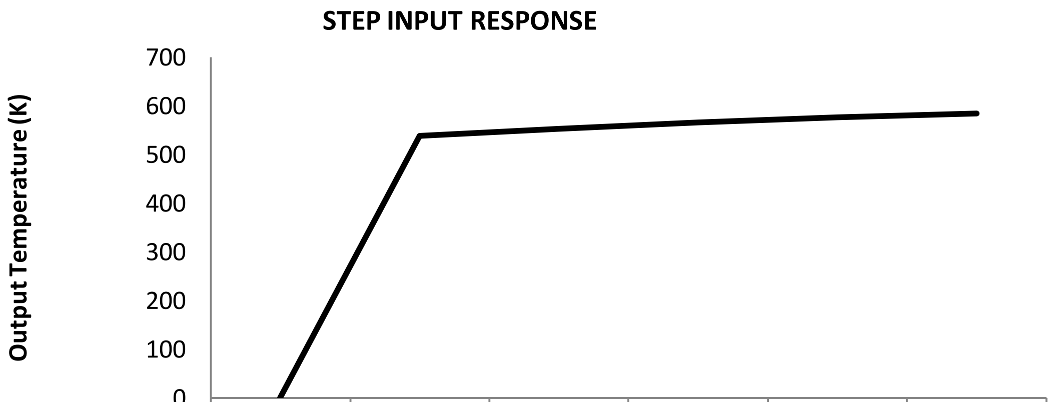
$$T_{0(s)} = A \quad (87)$$

$$T_{(s)} = \frac{KA}{(\tilde{\iota}s-1)} \quad (88)$$

$$T_{(t)} = KAe^{-t/_{\tilde{t}}} \quad (89)$$

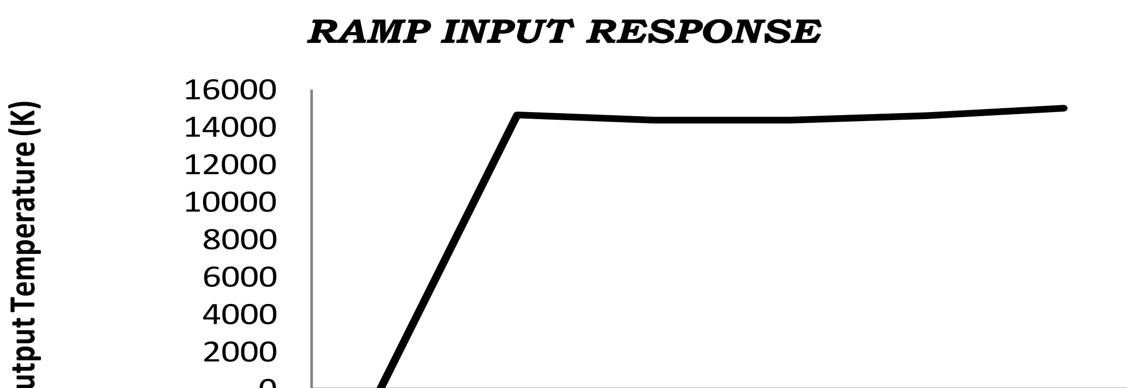
RESULTS AND DISCUSSION

The results obtained from the investigation are presented in Figures 2 to 7 and Tables 3 and 4. Figure 2 illustrates the output temperature T(t) response versus time for step input response. Increase in output temperature T(t) response was observed within a time range of above 0 to 20 s and after then a slight increase in output temperature was seen with increase in time. The variation in the output temperature T(t) response can be attributed to the variation in time. A linear change was observed within 0 and 20 s before experiencing functions that change instantaneously from one level to another within the range of 20 to 28 s. Comparing the results obtained from this investigation with desired value of 623 K



	t (s)	20	22	24	26	28
STEP INPUT	0	538.9	553.8	566.3	576.9	585.1

Figure 2. Graph of Furnace Output temperature T(t) responses versus Time for Step Input Response.



	t (s)	20	22	24	26	28
RAMP INPUT	0	14,661.	14,379.	14,373.	14,595.	15,002.

Figure 3. Graph of Furnace Output temperature T(t) responses versus Time for Ramp Input Response.

(which is the operating temperature for a functional furnace of Nigerian Liquefied Natural Gas (NLNG)), indicates that step input response characteristic or principle was used in designing the process temperature sensor in the furnace, which is close when compared to the calculated value of 585.1 K at 28 s from my investigation. For operating system of a furnace within the temperature range of slightly above 623 K and slightly below 623 k, a step input response is recommended for more accurate result.

Figure 3 illustrates the output temperature T(t) response versus time for ramp input response. A temperature response T(t) similar to step input was observed within a time range of above 0 to 20 s just but this occurs at a higher temperature range and after then a slight increase in output temperature was seen with increase in time. The variation in the output temperature T(t) response can be attributed to the variation in time. A linear change was observed within 0 and 20 s before experiencing functions that change instantaneously from one level to another within the range of 20 to 28 s. Comparing the results obtained from this investigation with desired value of 623 K, it indicates that ramp input response characteristic or principle cannot be used in designing the process of temperature sensor for a crude oil preheating furnace but can be used in high temperature operating furnaces such as the one used in pyrolysis with its value of 15,002 K at 28 s. For operating system of a furnace within the temperature range of slightly above 15,000 K and slightly below 15,000 K, a ramp input response is recommended for more accurate result.

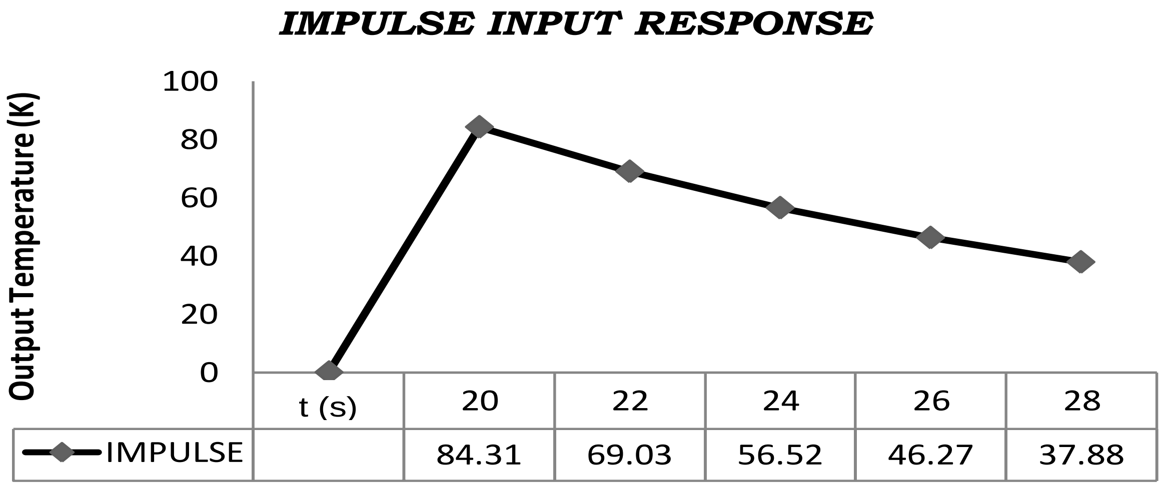


Figure 4. Graph of Furnace Output temperature T(t) responses versus Time for Impulse Input Response.

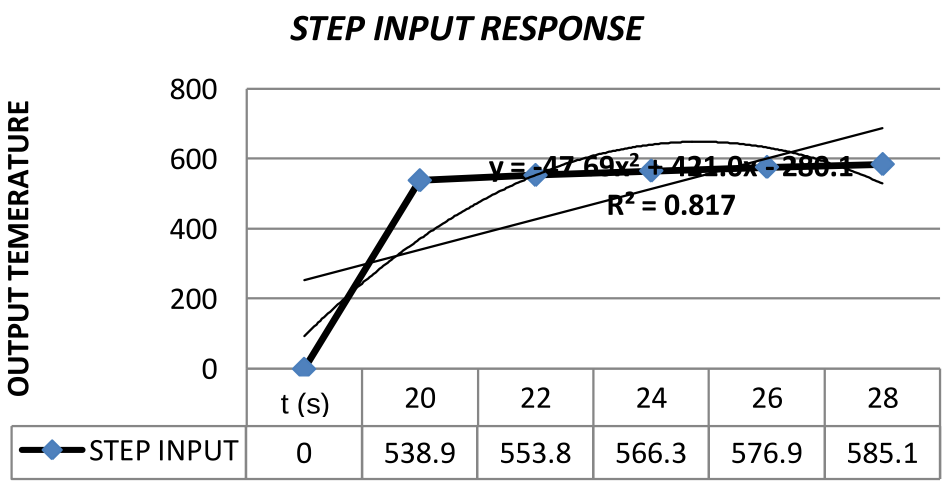


Figure 5. Graph of Furnace Output temperature T(t) responses versus Time for Step Input Response using polynomial and linear trend.

From Figure 4, it is seen that increase in output temperature T(t) responses was observed with increase in time within the range of above 0 to 20 s. The optimum output temperature T(t) responses were experienced at 20 s with the value of T(t) at 84.31 K. A decrease in output temperature was observed with increase in time indicating that the variation in the output temperature T(t) can be attributed to the variation in time as shown in Figure 4. The Figure 4 illustrates the principle of the impulse function, that is, the dirac delta function, an infinitely high pulse whose width is zero and area is unity. For operating system of a furnace within a temperature range of slightly 85.0 K and below, an impulse response is recommended for the design of the furnace for effective utilization and for more accurate result to be achieved at the end of the process.

Figure 5 illustrates the polynomial expression of output temperature T(t) responses for a step input operation. The equation of the polynomial is given as $47.69x^2 + 421.0x - 280.1$ and the square root of the curve is $R^2 = 0.817$.

Figure 6 illustrates the polynomial expression of output temperature T(t) responses for a ramp input operation. The equation of the polynomial is given as $-1236x^2 + 10794x - 694$ and the square root of the curve is $R^2 = 0.770$.

Figure 7 illustrates the polynomial expression of output temperature T(t) responses for a impulse input operation. The equation of the polynomial is given as $0.286x^2 - 19.53x + 360.2$ and the square root of the curve is $R^2 = 0.999$.

The output temperature decreases with increase in

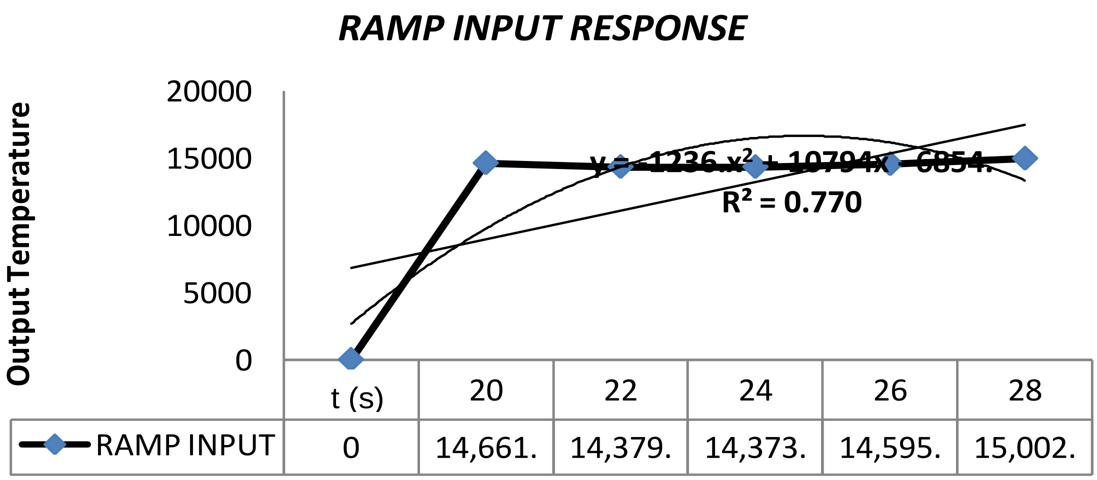


Figure 6. Graph of Furnace Output temperature T(t) responses versus Time for Ramp Input Response using polynomial and linear trend.

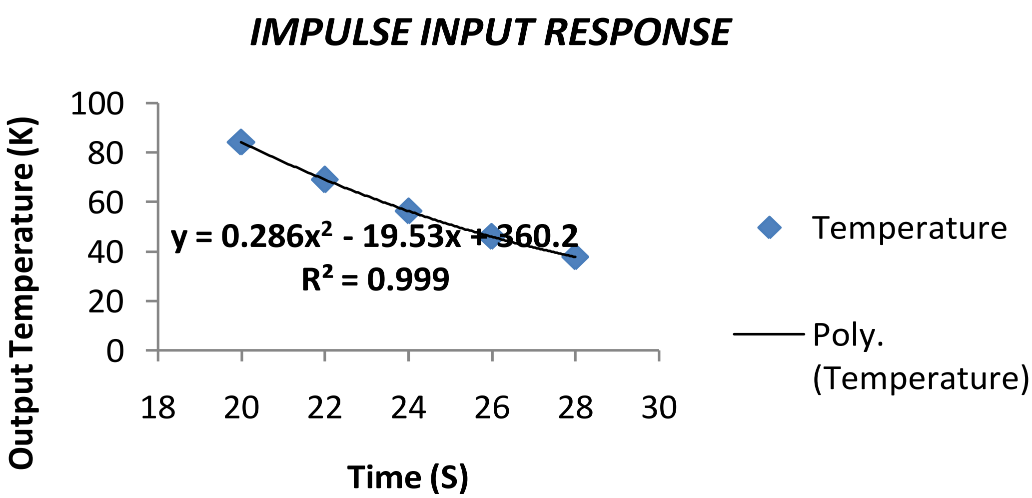


Figure 7. Graph of Furnace Output temperature T(t) responses versus Time for Impulse Input Response using polynomial and linear trend.

time at constant coefficient of time as presented in Table 3. A coefficient of time interval of two steps incremental starting from 6 to 14 s^{-1} was used to monitor the drop in output temperature of the furnace using different types of response as presented in the research work at constant time of 10 s.

The result presented in Table 4 illustrates the output temperature of the feed in the furnace at different time coefficient interval with constant time. An increase in output temperature was observed with increase in time at constant coefficient of time. A time interval of two steps incremental starting from 20 to 28 s was used to monitor the drop in output temperature of the furnace using different types of response as presented in the research work with constant coefficient of time (10 s^{-1}).

Conclusion

This work represents the first step in an overall study of the refinery separation train; a relatively simple non-linear model has been developed to describe the furnace dynamics. The dynamics of the furnace are controlled by thermal accumulation in the furnace walls and the dynamic response of the fluid in the radiation section. Thus, our system is described by three dynamic equations, resulting from an energy balance on the furnace walls and from mass and energy balances on the crude flowing in the radiation section. As a simplification the air supplied to the furnace has been considered as stoichiometric.

As an approximation to the non-linear model, linear

Table 3. Computation of furnace output temperature of crude oil at different values of time and coefficient of time.

S/No	Time (s)	τ (s^{-1})	$T_{L(t)}$
1	20	6	1,256.08
		8	523.78
		10	304.68
		12	209.10
		14	157.99
2	22	6	1,756.02
		8	674.10
		10	373.07
		12	247.85
		14	182.53
3	24	6	2,453.86
		8	867.28
		10	456.58
		12	293.39
		14	211.04
4	26	6	3,427.59
		8	1,114.88
		10	588.62
		12	347.25
		14	244.16
5	28	6	4,786.30
		8	1,435.04
		10	683.22
		12	410.70
		14	281.91

Table 4. Computation of furnace output temperature of crude oil at different values of time and coefficient of time.

Response	Time (s)	τ (s^{-1})	$T_{L(t)}$ (K)
Step input	10	20	538.9
		22	553.8
		24	566.3
		26	576.9
		28	585.1
Ramp input	10	20	14,661.39
		22	14,379.04
		24	14,373.73
		26	14,595.24
		28	15,002.47
Impulse	10	20	84.31
		22	69.03
		24	56.03
		26	46.27
		28	37.88

reduced model have been constructed to describe the effect of fuel flow rate and of disturbances in the inlet temperature and crude mass flow rate on the furnace output temperature. This linear model have been used to test different input response functions to see which one gives the closest output temperature when compared to the desired value. The results indicate that step input response gives the best and closest furnace output temperature of 525.1 K as compared to the desired value of 623 K at 28 s.

Nomenclature

ℓ_L : Density of liquid (crude oil) (kg/m^3)
$\dot{m}_{oil}$: Mass flow rate of oil (kg/h)
K_c : Constant of proportionality
T_o : Inlet temperature of crude oil to the furnace (K);
q_s : Heat input to the furnace (KW/m^2h)
A_{cp}: Cold plane area of tubes (m^2)
C_L: Specific heat capacity of liquid (crude oil) (J/kgK)
H_c^o : Enthalpy of combustion (KJ/ kgK)
H_f^o : Enthalpy of formation (KJ / kgK)
Q_{Rad} : Radiant heat transfer (W)
T_D : Desire output temperature of crude oil (K)
T_L : Output temperature of fuel gas (K)
T_G : Temperature of fuel gas (K)
T_{htc}: Temperature of heat transfer component (K)
T_t : Temperature of tube surface (K)
V_L : Volume of liquid (crude oil) (m^3)
F : Radiation exchange factor
UA : Heat transfer coefficient of furnace wall per unit area (W/m^2k)
α : Absorption efficiency factor
τ : Time constant of the furnace (^{1}/h)
σ : Stefan Boltzmann constant (W/m^2k^4).

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