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Design of a Medium Velocity Spray System for the Storage of Petroleum Products.

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ABSTRACT: *Process industries require efficient system of storage and safety of the equipment, environment and personnel. The possible hazards are a function of both the intrinsic nature and the involved volume of the petroleum product and irregular temperature rise. As heat is added to a system, molecular motion increases which result in the system experiencing an increase in temperature. The temperature sensor on detecting the sharp rise in the temperature characteristics triggers the valve for the hydrants to open and a cooling fluid to be showered on the storage tank of the petroleum product. The designed system ensures a continuous showering of a cooling fluid on the storage tank of the petroleum product once there's an increase in the products temperature thereby cutting off the occurrence of smoldering which could eventually result into a fire outbreak.*

KEYWORDS *Cooling Fluid, Fire, Petroleum, Temperature, Storage*

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I. INTRODUCTION

Petroleum and chemical products are essential resources of our time and are considered as one of the important basic building blocks for sustainable development. The increase in demand of hazardous chemicals has brought significant risk to man and its environment. Hazardous chemicals have intrinsic hazards for the environment, which may result in destruction of humans and properties within the accident zone [1]. The Occupational Safety and Hazard Administration (OSHA) has defined a hazardous chemical as any chemical which has a physical hazard such as health hazard (acute or chronic effects) or (fire and explosion) [2]. The historical analysis of major accidents in the chemical industries have shown that 17% of the accidents were during storage processes [3]. According to the National Fire Protection Association (NFPA) 2009 report, 13% of the worldwide fire accidents took place in storage tank farm causing injury or death for workers, millions of dollars losses and huge environmental pollution [4]. Many catastrophic casualties occurred in history such as the Bhopal disaster of 1984 which caused thousands of fatalities and thousands of people were injured. The possible hazards are a function of both the intrinsic nature and the involved volume of the chemical and irregular temperature rise [5].

Fire or explosion preventive measures at production sites, workplaces, storing or the use of flammable liquids can be guaranteed by complying with the Dangerous Substance and Explosive Atmosphere Regulations 2002 [6]. The main essence of the (DSEAR) is to ensure the safety of personnel and as many who may be at risk as a function of the disastrous substances that can cause explosion, fire and similar energy releasing event such as a runaway exothermic reaction [7]. Also, the increase demand for local content in the oil industries is a practical motivation for indigenous entrepreneurs to explore the opportunities available in the industry. Besides, every developing countrylike Nigeria is striving to ensure that there is technological advancement in their country.

The terminal 1 tank farm of Erohdyn Controls Ltd received product into its tank 2. A pig which was stuck in the cargo line for about 3 months did not impede the receipt of product since the pig was stuck a point not obstructing product flow as it is a common occurrence for the pig to be stuck inside two particular valves in the terminal. The pig retrieval process involved closing the Emergency Shutdown Valves (ESV) and pressurizing the line up to 10 bars and then opening the ESV to release the air into the pipeline, although the pig retrieval attempt was made unsuccessfully. There has been an ongoing hot work on tank 4 which involves drilling holes in the walkway platforms to aid drainage of water.

The product volume in tank 2 has risen to 7.6ML, although within safe operating limit of 8.5ML. The abundance of Oxygen and the simultaneous but unrelated events of pig retrieval and repair of tank 4 was believed to have aid the self-ignition of the premium motor spirit (PMS) product resulting into an inferno that lasted for 20hrs and the mega loss of 7.6ML of tank 2 product vol.

Factors which have caused fire accidents in tank farms and other storage facilities of process industries are as follows [8].

a. **More pressure inside the storage tank:** This is caused by;
   i. Tank exposed to an external heat source.
   ii. Outlet pipe of the storage tank blocked during transfer.
   iii. Failure of the automatic pressure control system.
   iv. Poor ventilation.
   v. Thermal expansion of oil in th
   vi. e storage tank due to strong sunlight.
   vii. Failure of the pressure relief valve

The consequence of more pressure is:

Possible explosion leading to an outbreak of fire as a result of the buildup of pressure in the tank, Pressure increases rapidly in the tank.

b. **More level in the storage tank:** This is caused by;
   i. The level indicator fails.
   ii. The alarm doesn't work properly.
   iii. The wrong valve opened.
   iv. Tank top unattended.
   v. Expansion of oil due to exposure to higher temperature.

The consequence of more level is:

Crude oil leakage to the atmosphere, which may initiate the fire if there is an ignition source. Consequently, due to exposure to heat radiation this may heat up the nearby tanks or cause burns to workers.

These factors enumerated could happen if the temperature of the tank is not properly control and regulated for effective storage purposes [9].

II. Fire Safety.

Fire is described as a very fast chemical reaction of oxidant with fuel which is accompanied by the release of energy and indicated by flame or incandescence [10].

A. Classification of Fire.

Fires are classified into the following, based on the category in which the fuel involve belongs;

i. *Class A Fires* — these are referred to as the solid combustible materials of organic nature such as paper, rubber, plastics, textile and wood.
ii. *Class B Fires* — the type of fire which involves flammable liquids such as gasoline, acetone, toluene, diethyl ether, alcohols.
iii. *Class C Fires* — the flammable gases under intense pressure e.g., liquefied gases.
iv. *Class D Fires* — combustible metals, such as potassium, magnesium, sodium etc.

B. Heat Transfer.

Heat transfer occurs during a fire by;

i. *Convection* **-** transfer of heat by the physical movement of hot masses of air.
ii. *Conduction* **-** transfer of heat which occurs within the material itself.
iii. *Radiation* **-** the emission of heat in the form of electromagnetic waves.

C. Combustion Characteristics.

The combinations of the following essential elements in their right proportion at the same time are necessary for the occurrence of fire;

i. Fuel or combustible material.
ii. Oxidizer to maintain combustion.
iii. Heat to activate ignition temperature.

The combine effect of these essential element in their right proportion resolves into a chemical chain reaction that initiates a fire. Hence, the removal of any of these elements douses out the fire [11].

The plate 1 shows a fire tetrahedron.

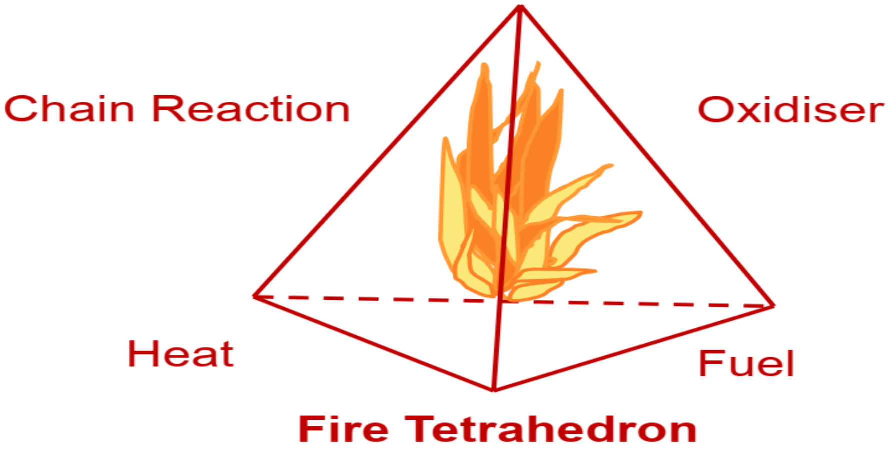

Plate 1: Fire Tetrahedron [12].

D. Dousing Fire.

Firecan be douse by the application of the following three major means [13].

i. Fire can be douse by releasing the water hydrant;Cooling the fuel by reducing the effect of radiant heat (e.g., by applying water).

Plate 2 shows the dousing of fire by water.

Plate 2: Dousing of fire by water [14].

ii. Fire can be douse by smothering the fire; occupying the air space thereby removing the supply of oxygen (e.g., by applying foam or carbon dioxide).

Plate 3 shows the dousing of fire by cutting off oxygen.

Plate 3: Dousing of fire by cutting off oxygen [14].

iii. Fire can be douse by depriving the fire; the removal of fuel. (e.g., stopping gas flow in a pipeline fire) and restraining the chain reaction from occurring. (e.g., applying dry chemical powder).

Plate 4 shows the dousing of fire by starving the fire of fuel.

Plate 4: Dousing of fire by starving the fire of fuel [14].

III. Methodology.

In designing the water-cooling system, dependent and independent variables have to be considered. Thus,

A. Dependent and Independent Variables.

The independent variables used are L (length), H (height), and W (width).Thedependent variables solved forare the velocities of the gas and liquid phases in the space directions when there is fire v_1, v_2, and u_l, u_2. The pressure **p,** which is assumed to be the same for both phases, the gas and liquid volume fractions $\mathbf{R_1}$and $\mathbf{R_2}$ as well as the “shadow” volume fraction $\mathbf{R_s}$. i.e., the volume fraction in the absence of evaporation, all other conditions being those evaluated with evaporation, the turbulence kinetic energy and its dissipation rate for the gaseous phase **k**and **E** and the concentration of water vapor C_l. The “shadow” volume fraction technique allows us to evaluate the diminishing droplet size during evaporation. Turbulence in the liquid phase is neglected.

B. The Mass Conservation Equation.

$$div(\rho_i R_i V_i) = S_i \quad (1)$$

$$R_g + R_l = I \quad (2)$$

Where;

I = Refers to the phase in question

g = For gas

l = Liquid

The volume fractions R_g and R_l need to satisfy the volume sharing condition.

$\mathbf{S}_i$ is the rate of evaporation for the gaseous phase and the liquid phase

C. The Conservation Equation for the General Variable δ.

The general source - balance equation for δ is,

$$div(\rho_i R_i V_i \delta_i - R_i \gamma_\delta grad\delta) = S_\delta \quad (3)$$

Where;

δ stands for the general dependent variables

γ is assumed constant from liquid phase to gaseous phase.

D. Inter Phase Friction Coefficient.

The two phases, gas and liquid slip with respect to each other resulting in the inter phase-friction force, as stated in equation (4).

$$F = D_C \rho B_P V_{slip} \quad (4)$$

Where;

ρ = Density of the gas phase.

D_c = Drag coefficient.

V_{slip} = The resultant slip velocity.
B_P = The total projected droplet area in the cell given by.

$$B_P = \left(1.5\frac{V}{d}\right) R_e \qquad (5)$$

Where;
d = the droplet diameter,
V = the volume of the cell,
R_e = the particle Reynolds number given by

$$R_e = d\frac{V_{SLIP}}{\alpha_i} \qquad (6)$$

Where;
α_i is the laminar viscosity of the gas.

The drag coefficient Dc is evaluated as follows;

$$D_c = max\left[0.42\frac{24}{R_e}(1 + 0.15R_e^{0.68}) + \frac{0.42}{1+(4.25\times10^4)R_e^{-1.16}}\right] \qquad (7)$$

E. Inter Phase Mass Transfer Coefficient.

As cooling of heated areas deals with evaporating water droplets, the loss of mass of the droplets needs to be calculated, see S_i in equation (1).

$$\dot{M} = \frac{A\sigma}{C_p D} ln\left(1 + C_p\frac{T_g - T_s}{L}\right) \qquad (8)$$

Where;
C_p = The specific heat, which is assumed to be constant for both phases.
D = The initial droplet diameter.
σ = The thermal conductivity of the water droplets.
L = The latent heat of evaporation.
T_g = The temperature of the gas.
T_s = The temperature at the surface of the droplet.
A = The interface surface area per cell given by.

$$A = \frac{6R_2V}{d} \qquad (9)$$

Where;
R_2 = the liquid volume fraction.
V = the cell volume.
d = the droplet diameter.

In the event of fire protection, adequate knowhow of the optimal droplet size is necessary in order to maximize the effectiveness of firefighting and improve the efficiency of the sprinklers. The major functionality of a sprinkler system is to douse out a fire as quickly as possible or to control its effect in the best possible way, it is also essential to use as few sprinkler heads as possible. Nevertheless, the discharge water droplet optimum size is dependent on specific criteria and requirements that should be put in place before installation [15].
Some of these criteria are as follows:

i. To prevent an excessive number of sprinklers from opening under the ceiling, cooling of the combustion products and ambient atmosphere is necessary.
ii. Wet and cool the walls subjected to direct exposure to fire and surrounding combustibles immediately.
iii. In order to extinguish the burning surface, the rising fire plume needs to be penetrated.

Therefore, large orifice sprinklers should be used, if greater penetrability of the drops through the plume is required.

F. Rate of Air Entrainment.

An approximated description of the whole air entrained by the sprays is given by the mono-dimensional models considering a finite element *dz*of the barrier:

$$\frac{da_1}{dz} = k_c 2l\rho_a v \qquad (10)$$

Where;

a_1 = Total mass flow rate of air entrained by the nozzle.
ρ_a = Air density in Kgm^{-3}
L = Width of curtain tunnel.
k_c = Entrainment constant.
z = Curtain axial coordinate.
v = Fluid velocity at distance z from the nozzle MS^{-1}

$$\frac{d}{dz}[(a_1 + s)v_1] = \frac{s}{v}g \qquad (11)$$

Where;

s = mass flow rate of sprays kgs^{-1}
g = acceleration due to gravity.

Equation (10) defines the global air entrainment. The balance of vertical momentum, Equation (11) is based on the assumptions that drops and entrained air are characterized by the same velocity, uniformly distributed on each horizontal section of the curtain. In particular, the right-hand side represents the force per unit length acting on the volume element dV≅b·l·dzof the curtain, being $dF_{oS}$the force acting on dV_1.

Note that;

F_{oS} = Mass force acting on the curtain, N.
ρ_2 = Density of the sprayed solution, Kg m^{-3}
b = Curtain width at distance z from the nozzle, m.

$$dF = (\rho_c - \rho_a)gdv_1 = \left\{\frac{a_1+s}{\frac{a_1}{\rho_a}+\frac{s}{\rho_2}} - \rho_a\right\}gdv = \frac{s\left(1-\frac{\rho_a}{\rho_2}\right)}{\frac{a_1}{\rho_a}+\frac{s}{\rho_2}} \equiv \frac{s}{blv}gbldz = \frac{sg}{v}dz \qquad (12)$$

Combining equations (10) and (11), we have;

$$\frac{dv}{dz} = \frac{sg - 2k_c l\rho_a v^3}{v(a_1+s)} \qquad (13)$$

Also, if we combine equation (10) and (13), we have;

$$\frac{da_1}{a_1+s} = \frac{v^2 dv}{v_2^3 - v^3} \qquad (14)$$

Where v_2 is defined as,

$$v_2 = \left[\frac{sg}{2k_c l\rho_a}\right]^{1/3} \qquad (15)$$

represents the value of vwhich makes up the drag and gravitational forces acting on the curtain.

$$2k_c\rho_a lv^2 = \frac{sg}{v} \qquad (16)$$

Therefore, integrating equation (14), on the assumption that $a_1(v_4) = 0$ then we have;

$$a_1 = s\left[\left(\frac{v_4^3 - v_2^3}{v^3 - v_2^3}\right)^{\frac{1}{3}} - 1\right] \qquad (17)$$

V_4 = Liquid velocity at the nozzle exit ms^{-1}

Substituting equation (17) in (13) gives,

$$\frac{dv}{dz} = -\frac{g}{v_2^3\left(v_4^3 - v_2^3\right)^{\frac{1}{3}}} \frac{\left(v^3 - v_2^3\right)^{4/3}}{v} \quad (18)$$

G. Water Spray System.

Automatic operation of the water spray system can be initiated by separate water filled detection piping when regular sprinkler heads are used as shown in the schematic diagram of the storage tank cooling system in plate 5.

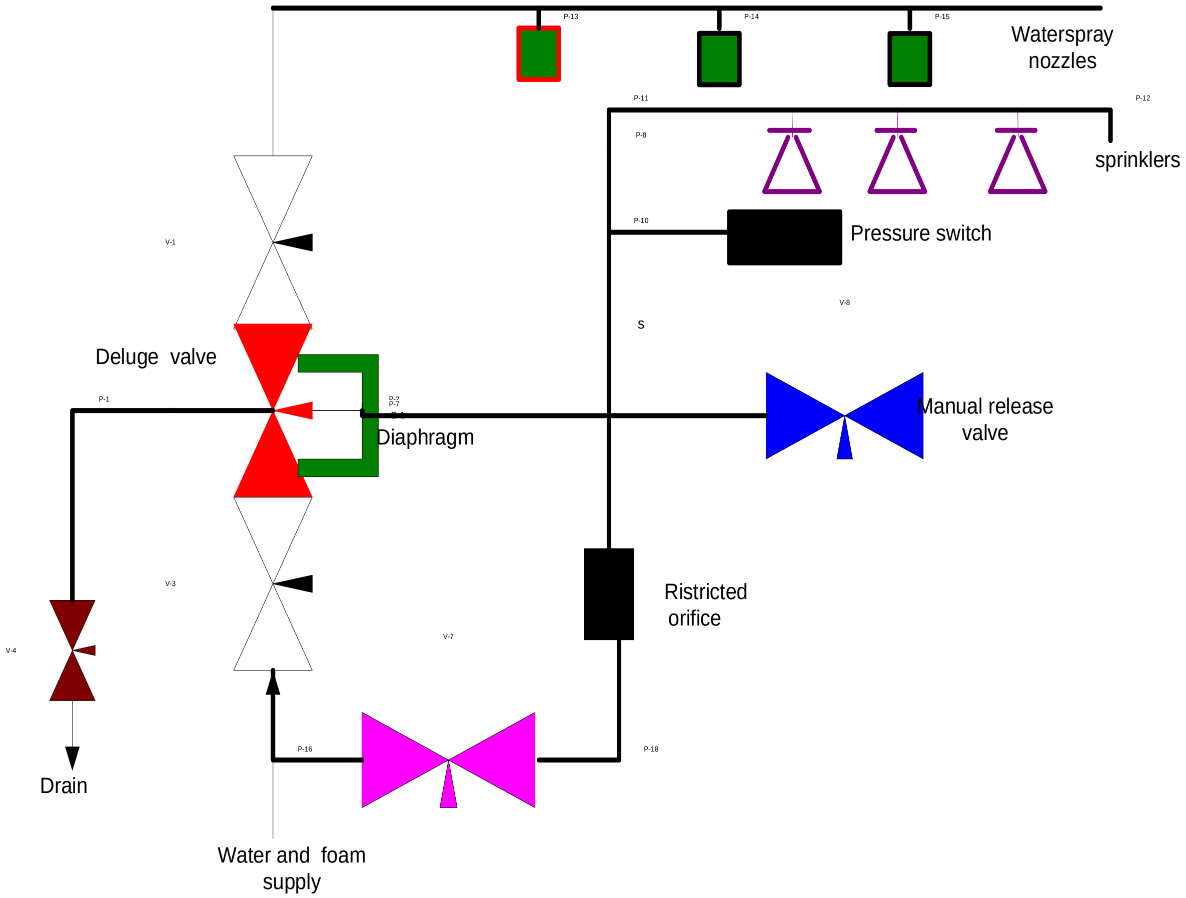

Plate 5: Storage Tank Water Spray System.

In this arrangement, detector sprinklers are fixed to a water charged pipe arrangement. A water tapping from below the lower isolating valve is connected through a restricted orifice valve to the array of sprinkler detectors and also to the deluge valve diaphragm. In the event of fire when one or more sprinkler detectors are activated, water from the tapping below the deluge valve through the restricted orifice cannot make up the flow discharging from the actuated detector sprinklers and thus the water pressure is released from the deluge valve diaphragm allowing the valve to open.Local manual release is provided by a valve on the sprinkler detection line and a pressure switch provides alarm indication. Sometimes a bypass valve is provided to enable local operation.

Within an automatic sprinkler installation, the type of sprinklers used are thermo sensitive, which are designed to react at predetermined temperatures and to function independently from one another. A mechanism is designed to open a valve and a stream of water is sprinkled over a given predetermined area once the preset temperature has been reached. The sprinklers head are placed at constant intervals away from one another and through a specially designed pipe system, the water travels to the sprinklers which are ordinarily over-headed. There are varieties of factors that should be put into consideration during the design of any sprinkler system. The operating temperature, speed of operation and the area which the spray umbrella will be covered are major factors of the design. The size of the sprinkler's orifice is used in determining the amount of water to be discharged as well as the pressure through which the water flows.

IV. RESULTS.

The simulation results obtained on the control of the storage tank temperature are as follows;

Figure 1 shows the simulation results of uncontrolled temperature and atmospheric effects

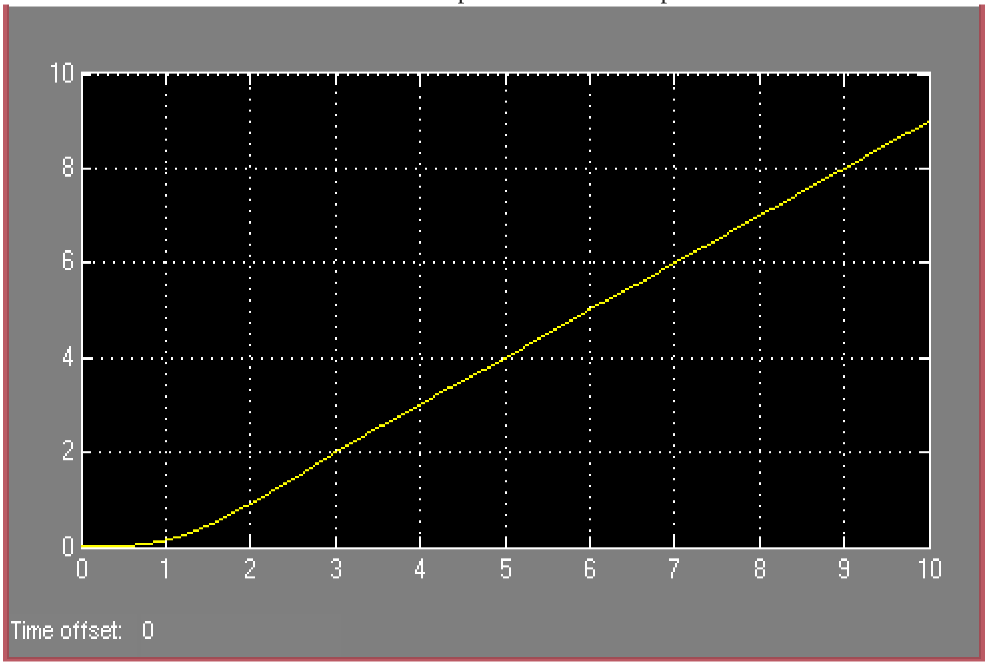

Fig. 1: Uncontrolled temperature deviation from set point.

Figure 2 shows the simulation results of controlled temperature and atmospheric effects

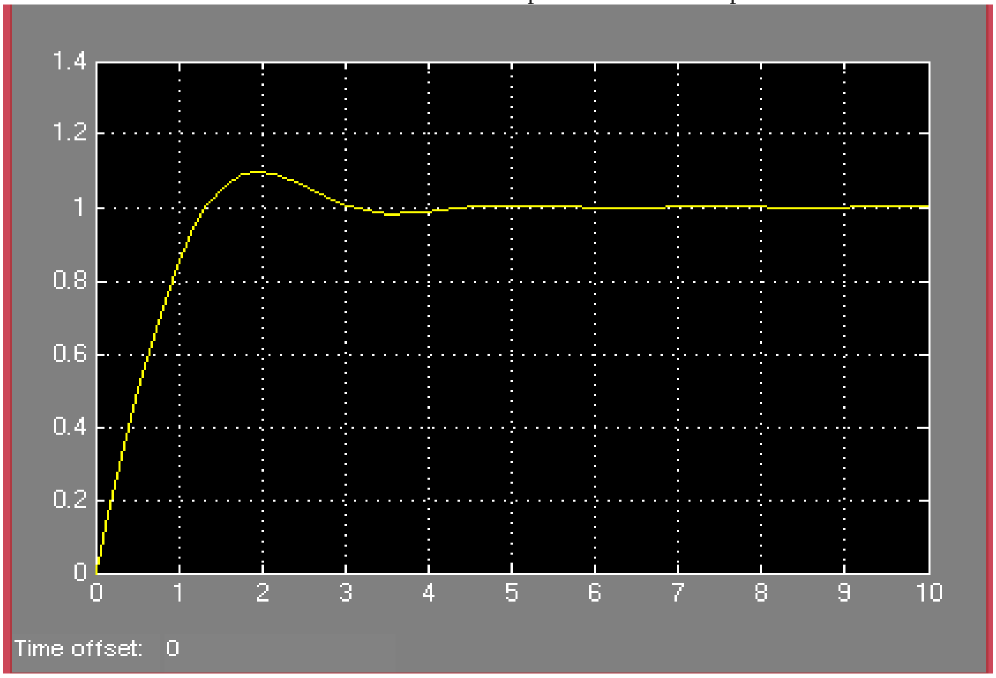

Fig. 2: Controlled temperature deviation.

Figure 1 and Table 1 which shows the simulated result of the uncontrolled characteristics of the thermal effect on the storage tank to be controlled. From the oscillogram, it can be seen that initially the graph was linear from the first point of storage, but as time goes by, the temperature of the storage tank increases linearly as the time progresses due to atmospheric conditions and internal agitations of the molecules of the fluid in consideration.

Figure 2 and Table 2 shows the real time effect of the control of temperature and atmospheric effect of the fluid. As the temperature tends to rise exponentially as a result of weather variations or agitation of the molecular particles of the fluid which causes an increase in the fluid temperature. The designed systems mitigate this increase in temperature thereby bringing it to a level that its safe for continuous storage of the fluid.

Table 1: Atmospheric condition and Effect on Temperature Characteristics

TIME (MINUTES)	TEMPERATURE (°C)
1	0.2
2	1.0
3	2.0
4	3.0
5	4.0
6	5.0
7	6.0
8	7.0
9	8.0
10	9.0

Table 2: Temperature Controlled Deviation

TIME (MINUTES)	TEMPERATURE (°C)
1	0.9
2	1.15
3	1.0
4	1.0
5	1.0
6	1.0
7	1.0
8	1.0
9	1.0

V. CONCLUSION

The sensor on detecting the rise in the temperature of a product gives a signal allowing the valve of the hydrants to open and a cooling fluid to be showered on the storage tank, thereby reducing the temperature of the product to a stable state. Unlike the control scheme in which an operator in the control room takes track record of the temperature characteristic of the product and immediately presses the fire alarm signal in the event of an increase in temperature. There is always an interval of time gap from the time of notification of the fire alarm because of the precautionary measures to be put in place by the safety and firefighters' personnel before their arrival at the storage facilities, it is this delay that often pave way for smoldering to take place and eventually result into a fire outbreak that could have been avoided with real time responses.

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