A Novel Design for Steam Generation System (SGS) from the Waste Heat Recovery of Hydrogen Production Plant

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Abstract

In this novel concept waste heat is recovered from the outlet process streams of primary reformer and high temperature shift convertor (HTSC) of the 1.5 ton/hr hydrogen gas plant at United Industries Limited (UIL), Faisalabad, Pakistan. Waste heat is utilized, and heat recovery steam generation (HRSG) system is designed. UIL's hydrogen gas plant with HRSG system is modelled and simulated on Aspen HYSYS. The heat recovery from UIL's hydrogen gas plant is used for generating steam of 1.5 MPa, 750 ^{o}C @ 1900 kg/hr flow. The steam generation system (SGS) has been proposed and installed at UIL's hydrogen gas plant where waste heat recoveries of 4.5 GJ/hr and 2.8GJ/hr from outlets streams of primary reformer and high temperature shift convertor has been obtained successfully.

Keywords: Aspen HYSYS, hydrogen gas plant, heat recovery steam generation (HRSG), Steam generation system (SGS), simulation

1. INTRODUCTION: -

United Industries Limited (UIL) is an independent refinery in Pakistan with capacity of 400 tons per day of edible oil, and fulfilling 3-4% consumption of edible oil at national level. The plant was commissioned in 1962 under government supervision of Pakistan with 50 tons per day capacity of ghee, and privatized in 1992 (UIL 2020). Hydrogen is the basic need of ghee industry, and utilized in the hydrogenation of vegetable oil to ghee. UIL's has its own hydrogen gas plant with capacity of 1.5 ton/hr (UIL 2020). Hydrogen gas plant is fortified with primary reformer (PR), high temperature gas shift converter (HTSC), low temperature gas shift converter (LTSC), absorption column and stripper. The energy optimization is the goal of every industry to

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minimize the energy loss, and to reduce the global warming effect by utilizing the waste heat (Colonna and van Putten 2007). The aim is to utilized the maximum waste heat of hydrogen gas plant for heat recovery steam generation (HRSG) system, while saving the steam for process pant. The waste heat from outlet streams of reformer and HTSC is recovered, and furthermore HRSG system is proposed and designed by the aid of process design and simulation software; Aspen HYSYS.

2. PROCESS DESCRIPTION: -

Natural gas is passed through desulfurizer in the presence of ZnO catalyst. Desulfurized natural gas is mixed with the steam of 1.5 MPa @ 210 ^{o}C, and maintaining ratio of 1:5 on molar basis. Mixed reformer feed is preheated in pre-heater up to approximately 530 ^{o}C before entering the reformer. The process gas enters at the top of the primary reformer tubes filled with nickel-based catalyst and process gas exit at the bottom with the temperature ranges from 630-930 ^{o}C. In the tubes, hydrocarbons and steam react endothermically to form H_2, CO, CO_2. The heat required to drive the endothermic reactions is provided by the combustion of fuel on the furnace side. On the furnace side, tubes are separated by rows of burners, and produces long flame that start at the top of the furnace and extended approximately half way down the tubes. Mixture of process effluent (H_2, CO, CO_2, H_2O, and CH_4) leaves the reformer, and cooled down up to 350 ^{o}C, and the portion of waste heat is rejected to the environment. The cooled process effluent is sent to the HTSC in which water-gas-shift reaction is used to convert CO and H_2O into CO_2 and H_2. The HTSC increases the amount of H_2 gas in the process stream. The process-side effluent at the outlet of HTSC is cooled up to 120 ^{o}C, and passed through the LTSC. The remaining conversion of CO to CO_2 and H_2 is take place in LTSC. The gas exiting the LTSC is sent to the MEA absorbing system after cooling where CO_2 is absorbed and hydrogen is sent

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to the hydrogenation section of the ghee plant. The purified hydrogen gas is the main product from the plant and purified carbon dioxide as a side product.

3. SIMULATION METHODOLOGY: -

In this study Aspen HYSYS was used to perform simulation of UIL's hydrogen gas plant for the recovery of heat. The two fluid packages i.e.; SRK EoS has been used for flash calculations while ASME Steam has been selected and used for the calculation of steam properties. It is further assumed that the heat required for isothermal reactor is provided by the combustion of natural gas in primary reformer and the pressure drop, heat losses are considered negligible during simulation calculations.

4. REACTION MECHANISM: -

The reforming of natural gas by the aid of steam is the process to create favorable conditions for the production of hydrogen gas. The production of hydrogen gas involves the series of reactions in the PR, HTSC, and LTSC. The methane-steam reactions mainly took place in primary reformer as shown in equations (1), (2), (3) and (4). The water-gas-shift reaction has been performed in HTSC and LTSC and presented in equation (5). The PR reactions are endothermic and reversible, and energy is provided to the reaction for maximum conversion of CH_4 to H_2, while on the other hand water-gas-shift reaction taking place in HTSC and LTSC are exothermic; and the temperature is reduced at both inlets to get maximum conversion of CO to CO_2 and extra H_2 to the system. This reduction in temperature is used to design HRSG system.

$$CH_4 + H_2O \rightarrow 3H_2 + CO \quad (1)$$

$$CH_4 + H_2O \rightarrow 4H_2 + CO_2 \quad (2)$$

$$C_2H_6 + 2H_2O \rightarrow 5H_2 + 2CO \quad (3)$$

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$$C_2H_6 + 4H_2O \rightarrow 7H_2 + 2CO_2 \quad (4)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (5)$$

5. MODELLING AND SIMULATION OF HEAT RECOVERY STEAM GENERATION (HRSG) SYSTEM: -

Waste heat can be generated as a result of combustion of various types of fuel or chemical reaction which is not used, and dumped to the environment from which no economic benefit is obtained. The heat recovery depends on the energy of process effluent and especially the economics involved. Hot gases evolve with large quantity of heat and these gases may be the exhaust of kilns, furnaces, boilers etc. and may be the process streams that are to be cooled. The considerable amount of heat that can be recovered results in the reduction of primary fuel consumption (Theodore L. Bergman , T. Reg Bott G. F. Hewitt 1994). Full recovery of waste heat from source may cannot be possible but most of the heat is recovered and thus minimize losses. The quality of waste heat must be considered before evaluating waste heat recovery. The waste heat can be discarded to the environment which depends upon the potential of the process whether it is from cooling media or heating media (Everett B. Woodruff 2020) . The assessment of the heat recovery can be analyzed on the basis of the requirement of the industries (Taplin 2020). The major assessment is done to control the greenhouse gas (GHG) emission to the environment as well as on the global warming issues (exergy-orc.com 2020, UIL 2020). The waste heat can be used for heating as well as cooling purposes. The WHR of the system is feasible with the outlet process stream of the reformer and HTSC, as the waste heat is wasted to the environment and streams are cooled with saturated steam (Weerasiri 2014). The following equations 6, 7 and 8 has been

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used for the calculations of heat capacities and the energy content of the stream.

$$Q = \dot{m} C p \Delta T \quad (6)$$

$$Q_{Reformer} = \dot{m} C p \Delta T \quad (7)$$

$Q_{Reformer}$ = (4174) × (2.644) × (800-350) = 4.9662252 GJ/hr

$$Q_{HTSC} = \dot{m} C p \Delta T \quad (8)$$

Q_{HTSC} = (4174) × (2.419) × (400-120) = 2.82713368 GJ/hr

Where $\dot{m}$ *= kg/hr, Cp = kJ/kg-C and* $\Delta T = {}^{o}C$

The heat recovery steam generation (HRSG) system is used to recover waste heat from hot exhaust or process stream. The temperature of hot media introducing into the HRSG system is usually in between 800 K to 1200 K. The industrial units are fully equipped with HRSG system for economical and optimization purposes. The HRSG system is entailed of superheater, evaporator, and economizer; moreover, there is no furnace and no fuel consumption. In HRSG system BFW is first passed through the economizer, then evaporator, and finally superheater for maximum possible heat recovery, while on the other side heating media is circulating. Heat transfer occurs through surface. The HRSG system is can be operated at single pressure or at multiple pressures. In our research work WHR possibility at UIL's pant site proposed, and HRSG system is modified according to the process requirements. UIL's entire plant require only saturated steam, and the HRSG system is limited to the evaporator and economizer for economical design.

Mostly economizers are used to preheat fluid such as water before entering the boiler (Weerasiri 2014). The economizer is located next to the evaporator in the HRSG design to recover the heat from the outlet of HTSC. The BFW is passed through economizer; conductive and convective heat was exchanged with

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the outlet process stream of HTSC. The BFW is heated below 373 K to prevent steam formation. The steam formation in economizer causes hammering and lowering the heat transfer coefficient. The heated BFW is then enters into the steam drum inside the boiler. The counter current flow is employed for the maximum heat transfer from the hot gases to the BFW. The concept of approach temperature is used in economizer to prevent the formation of steam, and the ΔT of heated BFW should be lower than saturation temperature (Jadhao 2013). The normal range of approach temperature is usually in between 273 to 293 K.

$$T_{App} = T_{sat} - T_{(e)out} \quad (9)$$

The various approaches have been used for the modelling of the economizer, first approach includes the formulation of the model equation by giving heat transfer area and coefficients, and the second approach includes the dimensioning parameters to find out the heat transfer area and to formulate model equation. The dimensioning parameters are known, and therefore model equation can be formulated easily. The product of the heat transfer coefficient and area can be calculated thus as follows:

$$Q = UA(LMTD) \quad (10)$$

$$LMTD = \frac{\left(\left(T_{hi}-(T_{sat}-T_{App})\right)-(T_{ho}-T_{ci})\right)}{ln\left(T_{hi}-(T_{sat}-T_{App})\right)/(T_{ho}-T_{ci})} \quad (11)$$

where, $\boldsymbol{T_{App} = T_{sat} - T_{(e)out}}$,

Thus

$$m_f(h_{out} - h_{in}) = UA\left(\frac{\left(\left(T_{hi}-(T_{sat}-T_{App})\right)-(T_{ho}-T_{ci})\right)}{ln\left(T_{hi}-(T_{sat}-T_{App})\right)/(T_{ho}-T_{ci})}\right) \quad (12)$$

The economizer simulated on the Aspen HYSYS and the plot is shown in Figure 3. In the plot, the approach temperature

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has been set to 3.29 °C. The heated BFW enters in evaporator at 370 K, and utilized latent heat of vaporization of process stream for steam generation. The evaporator area and steam generation capacity depend on pinch point ΔT. UIL's hydrogen plant parameters are known so the approach of pinch point ΔT would be suitable for modelling and simulation of evaporator. The general equation of heat transfer can be modeled for this evaporator which is shown below.

$$UA\left(\frac{((T_{hi}-T_{co})-(T_{ho}-T_{ci}))}{ln(T_{hi}-T_{co})/(T_{ho}-T_{ci})}\right) = m_{bfw}\left(h_{sat,vap}-h_{in}\right) \quad (13)$$

where the pinch-point, is defined in the saturated region; $P_P = T_{ho} - T_{ci}$

In the model equation the product of UA is compensate the effect of fouling in evaporator. The incoming heated BFW water from the economizer is below saturation temperature due to approach point ΔT was set for economizer. The modelling of evaporator utilized pinch point ΔT and cooled the inlet of HTSC up to 623 K. It can be seen in the simulation results of Aspen HYSYS plotted as shown in Figure 5.

6. CONCLUSION: -

In this modelling and simulation research work, feasible HRSG system is proposed and designed for UIL's hydrogen gas plant. HRSG system components were reduced according to the need of the hydrogen gas plant. The first feasible WHR section at the outlet of reformer, and the second at the outlet of the HTSC. Both the evaporator and economizer simulated on process simulator i.e.; Aspen HYSYS. The modelling of economizer and evaporator on the basis of approach temperature and pinch point temperature. The final simulation results for HRSG system shows that excess heat of 4.5 GJ/hr could be recover from reformer outlet stream and 2.8GJ/hr from HTSC outlet stream.

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TABLES AND FIGURES: -

Table 1: Aspen HYSYS simulation base-case material balance sheet for UIL's hydrogen gas plant without heat recovery steam generation (HRSG) system

Stream #	Stream Name	T (K)	P (MPa)	Stream Phase	Volume Flow Rate (m^3/hr)						
					H_2	CH_4	C_2H_6	CO	CO_2	H_2O	Total
1	Steam	473	1.50	V	--	--	--	--	--	3.6102	3.6102
2	Natural gas feed	303	0.50	V	--	1.4339	0.0062	--	0.1689	--	1.6090
3	Mixed feed	435	0.50	V	--	1.4339	0.0062	--	0.1689	3.6103	5.2192
4	Reformer feed	773	0.49	V	--	1.4339	0.0062	--	0.1689	3.6103	5.2192
5	Reformer outlet	1073	0.49	V	2.8679	--	--	0.2865	1.1677	2.7864	7.1085
6	HTSC inlet	623	0.30	V	2.8679	--	--	0.2865	1.1677	2.7864	7.1085
7	HTSC outlet	673	0.30	V	3.0802	--	--	0.0286	1.5600	2.6536	7.3225
8	LTSC inlet	393	0.25	V	3.0802	--	--	0.0286	1.5600	2.6536	7.3225
9	LTSC outlet	473	0.25	V	3.0920	--	--	0.0143	1.5818	2.6462	7.3344

Table 2: Aspen HYSYS simulation base-case energy balance sheet for UIL's hydrogen gas plant without heat recovery steam generation (HRSG) system

Stream #	Stream Name	T (K)	P (MPa)	Stream Phase	Volume Flow Rate (m^3/hr)						
					H_2	CH_4	C_2H_6	CO	CO_2	H_2O	Total
1	Steam	473	1.50	V	--	--	--	--	--	3.6102	3.6102
2	Natural gas feed	303	0.50	V	--	1.4339	0.0062	--	0.1689	--	1.6090
3	Mixed feed	435.3	0.50	V	--	1.4339	0.0062	--	0.1689	3.6103	5.2192
4	Reformer feed	773	0.49	V	--	1.4339	0.0062	--	0.1689	3.6103	5.2192
5	Reformer outlet	1073	0.49	V	2.8679	--	--	0.2865	1.1677	2.7864	7.1085
6	HTSC inlet	623	0.30	V	2.8679	--	--	0.2865	1.1677	2.7864	7.1085
7	HTSC outlet	673	0.30	V	3.0802	--	--	0.0286	1.5600	2.6536	7.3225
8	LTSC inlet	393	0.25	V	3.0802	--	--	0.0286	1.5600	2.6536	7.3225
9	LTSC outlet	473	0.25	V	3.0920	--	--	0.0143	1.5818	2.6462	7.3344
10	Feed heater outlet	372	0.24	V + L	3.0920	--	--	0.0143	1.5818	2.6462	7.3344
11	BFW	298	0.10	L	--	--	--	--	--	1.9033	1.9033
12	Heated BFW	372.3	0.099	V + L	--	--	--	--	--	1.9033	1.9033
13	Exporting steam	1004	1.5	V	--	--	--	--	--	1.9033	1.9033

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Table 3: Aspen HYSYS simulation material balance results for UIL's hydrogen gas plant with heat recovery steam generation (HRSG)

Stream #	Stream Name	T (K)	P (MPa)	Phase Fraction		Heat Flow (kJ/hr)						
				L	V	H_2	CH_4	C_2H_6	CO	CO_2	H_2O	Total
1	Steam	473	1.50	--	1	--	--	--	--	--	- 4.732 e7	- 4.732 e7
2	Natural gas feed	303	0.50	--	1	--	- 2.903 e6	- 8.137 e3	--	- 0.343 e6	--	- 3.255 e6
3	Mixed feed	435.3	0.50	--	1	--	- 5.882 e6	- 15.17 e3	--	- 0.698 e6	- 43.98 e6	- 5.058 e7
4	Reformer feed	773	0.49	--	1	--	- 5.530 e6	- 14.26 e3	--	- 0.656 e6	- 41.34 e6	- 4.755 e7
5	Reformer outlet	1073	0.49	--	1	- 13.68 e6	--	--	- 1.12 e6	- 3.016 e6	- 21.25 e6	- 3.908 e7
6	HTSC inlet	623	0.30	--	1	- 15.33 e6	--	--	- 1.26 e6	- 3.380 e6	- 23.81 e6	- 4.379 e7
7	HTSC outlet	673	0.30	--	1	- 16.39 e6	--	--	- 0.12 e6	- 4.493 e6	- 22.57 e6	- 4.358 e7
8	LTSC inlet	393	0.25	--	1	- 17.41 e6	--	--	- 0.13 e6	- 4.773 e6	- 23.98 e6	- 4.630 e7
9	LTSC outlet	473	0.25	--	1	- 18.34 e6	--	--	- 63.7 e3	- 5.077 e6	- 25.09 e6	- 4.556 e7

Table 4: Aspen HYSYS simulation energy balance results for UIL's hydrogen gas plant with heat recovery steam generation (HRSG) system

Stream #	Stream Name	T (K)	P (MPa)	Phase Fraction		Heat Flow (kJ/hr)						
				L	V	H_2	CH_4	C_2H_6	CO	CO_2	H_2O	Total
1	Steam	473	1.50	--	1	--	--	--	--	--	- 4.732 e7	- 4.732 e7
2	Natural gas feed	303	0.50	--	1	--	- 2.903 e6	- 8.137 e3	--	- 0.343 e6	--	- 3.255 e6
3	Mixed feed	435.3	0.50	--	1	--	- 5.882 e6	- 15.17 e3	--	- 0.698 e6	- 43.98 e6	- 5.058 e7
4	Reformer feed	773	0.49	--	1	--	- 5.530 e6	- 14.26 e3	--	- 0.656 e6	- 41.34 e6	- 4.755 e7
5	Reformer outlet	1073	0.49	--	1	- 13.68 e6	--	--	- 1.12 e6	- 3.016 e6	- 21.25 e6	- 3.908 e7
6	HTSC inlet	623	0.30	--	1	- 15.33 e6	--	--	- 1.26 e6	- 3.380 e6	- 23.81 e6	- 4.379 e7
7	HTSC outlet	673	0.30	--	1	- 16.39 e6	--	--	- 0.12 e6	- 4.493 e6	- 22.57 e6	- 4.358 e7
8	LTSC inlet	393	0.25	--	1	- 17.41 e6	--	--	- 0.13 e6	- 4.773 e6	- 23.98 e6	- 4.630 e7
9	LTSC outlet	473	0.25	--	1	- 18.34 e6	--	--	- 63.7 e3	- 5.077 e6	- 25.09 e6	- 4.556 e7
10	Feed heater outlet	372	0.24	0.8217	0.1783	-18.34 e6	--	--	- 68.0 e3	- 5.077 e6	- 25.09 e6	- 4.859 e7
11	BFW	298	0.10	1		--	--	--	--	--	3.019 e7	- 3.019 e7
12	Heated BFW	372	0.099	0.5126	0.4874	--	--	--	--	--	- 2.746 e7	- 2.746 e7
13	Exporting steam	1004	1.5		1	--	--	--	--	--	- 2.275 e7	- 2.275 e7

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M-100	E-100	R-100	R-101	R-102	E-101	E-102
Feed mixer	Feed preheater	Primary reformer	HTSC	LTSC	HTSC cooler	LTSC cooler

M-100	E-100	R-100	R-101	R-102	E-102	E-103
Feed mixer	Feed preheater	Primary reformer	HTSC	LTSC	Economizer	Evaporator

Figure1: Base case Aspen HYSYS flowsheet for UIL's hydrogen gas plant without heat recovery steam generation (HRSG) system

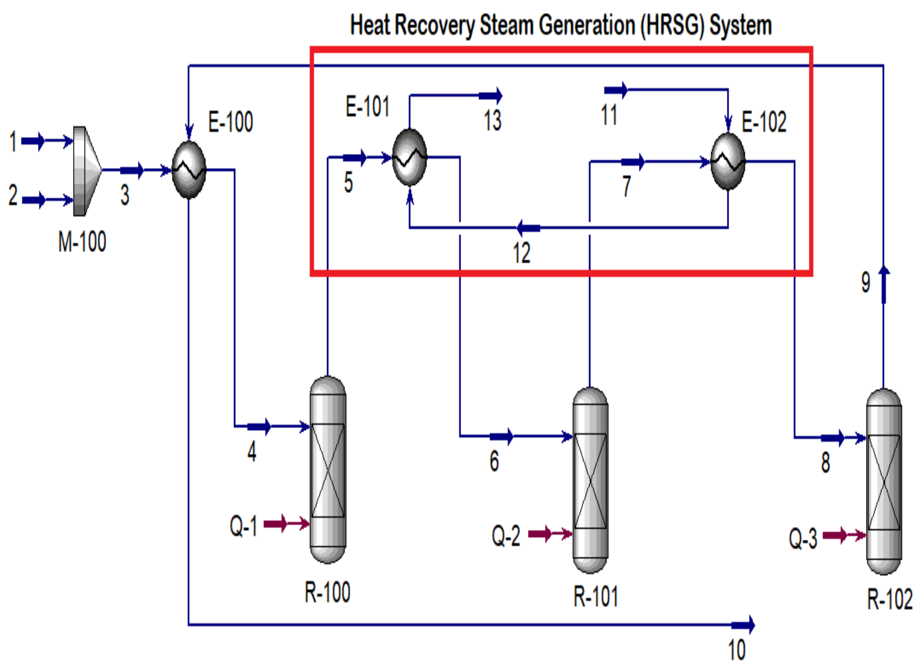

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Figure 2: Aspen HYSYS flowsheet for UIL's hydrogen gas plant with heat recovery steam generation (HRSG) system

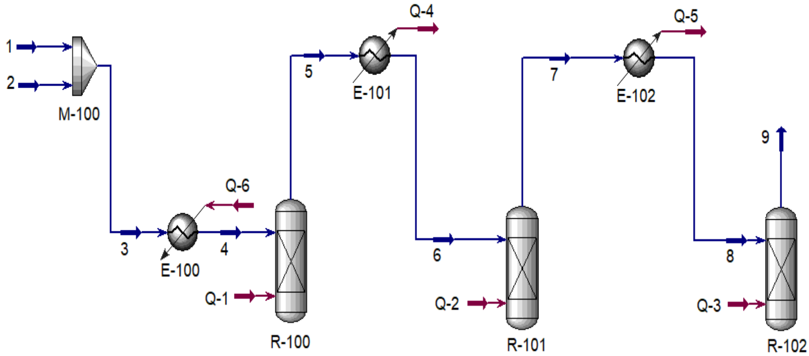

Figure 3: Approach temperature demonstration

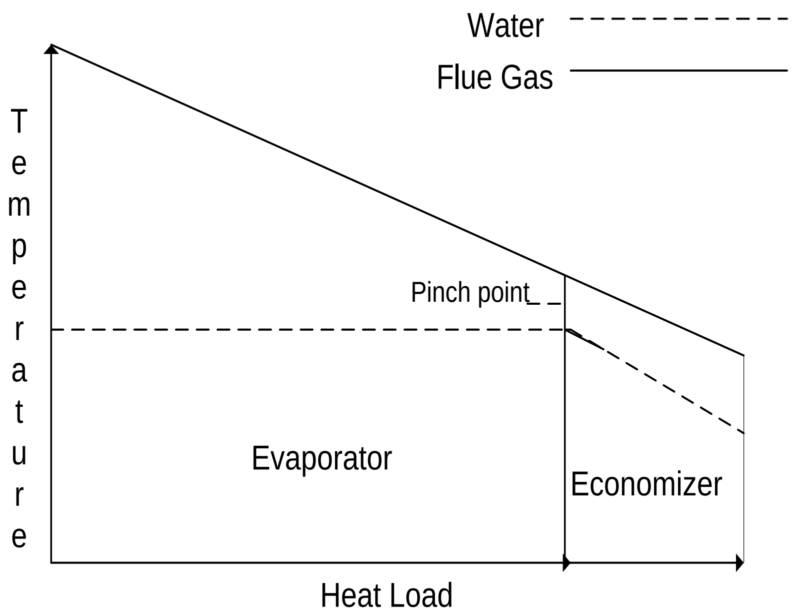

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Figure 4: Heat load graph showing pinch point

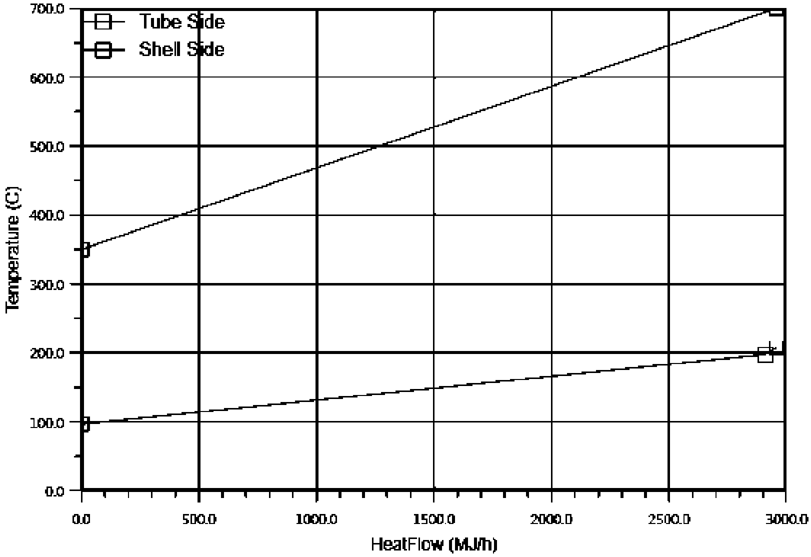
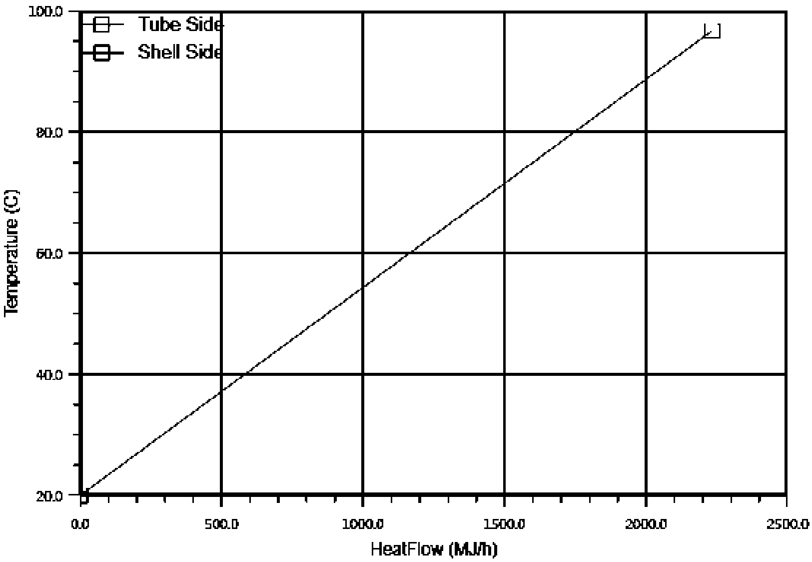


Figure 5: Pinch point demonstration



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