International Journal of Electrical Energy, Vol. 4, No. 1, March 2016

Energy Recovery from Air Compressors in a Semiconductor Plant Using Plate Heat Exchanger

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Abstract—**An experimental analysis based on the heat transfer principle is carried out in this paper for recovery of the heat energy in the semiconductor plant from the hot compressed air together with cold water using a plate heat exchanger. The primary objective of this analytical study is to facilitate consumers and society in terms of providing an eco-friendly mechanism possessing low manufacturing cost. This scheme of heat energy recovery from air compressor is related to energy and monetary savings, gained through low consumption of diesel oil and electricity, low value of carbon emission content, and lower maintenance cost, verified from the usage data of compressed air, water and energy, from relevant unit operation of a semiconductor plant production facility. On examining the case study, it is envisaged that an estimated amount of energy saving is about 202,703kWh per year, that can be achieved through simultaneous saving in other attributes such as diesel oil of 36,500 liters per year, i.e. no longer exist in the proposed method, carbon emission content of 207,685kg CO_2 per year, and maintenance cost of about 180,000 Baht per year, with a fast payback period of 1.5 years. Several numerical examples are presented for ensuring the validity of the proposed model. The results obtained are compared to other existing method of the heat energy recovery, showing a significant potential benefits in energy recovery.**

Index Terms—**air compressor, energy savings, heat energy recovery, plate heat exchanger**

I. INTRODUCTION

Environmental friendly, sustainable growth and energy security are taken primarily into consideration worldwide. Several industries suffer from an increasing pressure to reduce their carbon footprint and, many companies are proactively taking steps in this direction. The facility support's plant sometimes, faces difficulty in regulating energy operation of the semiconductor plant effectively in order to extract out as much productivity, corresponding to every single unit of energy that is consumed and being charged. Shah *et al.* [1] termed a heat exchanger as a device that is used to transfer thermal energy between two or more fluids at different temperatures and are in thermal contact. Now, it became an essential component used in several industrial processes, and the benefits associated with this derive from its use. Some common applications are: refrigeration, air conditioning, heating, power plants, chemical plants, petrochemical plants, waste heat recovery, transportation, and manufacturing industries, etc., which also serves as the basis for their classification. These classifications are as follows: mechanisms of heat transfer, constructional features, the degree of surface compactness, number of fluids and flow arrangements. Noah Yakah [2] has made a discussion on the classification of heat exchanger based on their constructional features.

There are basically four major constructional features by which heat exchangers can be classified, namely (i) tubular in which the most common type is the shell-and-tube, (ii) plate-type or primary surface remunerators including plate, spiral, plate coil and printed circuits, (iii) an extended surface including plate-fin and tube-fin, and (iv) regenerators including rotary, fixed matrix and rotating hood.

The shell-and-tube type heat exchanger has been used for many decades because of its numerous advantages, e.g. variety in terms of installation which means the demanded horizontal or vertical, leakages in the tube which can be detected easily with the use of pressure test, and the heat transfer which can be enhanced by incorporating an extended heat transfer surface. Some of the common disadvantages associated with this type of heat exchanger are high-priced, less efficient in heat transfer, and the requirement of a large amount of space.

Jeong *et al.* [3] discussed the beneficial aspects of the plate heat exchanger such as the improved effectiveness, i.e. 90% or more, lower installation cost, and application based flexibility. The main disadvantage associated with this type of heat exchanger is its highly priced preventive maintenance required for gasket replacement. McDonald [4] applied the plate heat exchanger to attain compactness usually by deploying secondary surfaces, or fin structures between plane partings. Another type of heat exchanger is Plate Flame Heat Exchanger (PFHE) used in three states, namely, liquid-liquid, liquid-gas, and gas-gas. Exchange of heat energy between the liquid-gas and hot air-water is used in this paper. The PFHE has advantages in terms of estimated effectiveness, greater than 90%, and maximum operating temperature and pressures of 650 ℃ and 120 bar, respectively. Aquaro *et al.* [5] proposed limitations subjected to the PFHE application, including longer braze cycle, high capital cost, complex programming associated with the manufacturing process, convoluted assembly,

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Manuscript received July 1, 2015; revised December 31, 2015.

doi: 10.18178/ijoee.4.1.17-23

material flexibility, and high repair rate. In addition, there are some issues raised by the PFHE use [6], i.e. difficult to repair, mostly if it leaks internally in the core region. The rotary heat exchanger has some advantages in terms of satisfactory heat transfer rate and high pressure. Apart from these advantages, some disadvantages are also presented as higher maintenance and repair cost, vibration and noise irritation. Principle of the heat energy recovery is usually being implemented in industrial plants such as cement factory [7], lignite-fired power plant [8], corn-ethanol plant [9], steel making plant [10], milk plant [11], coffee roasting plant [12], refrigeration plant [13], Sulphuric acid plant [14], and tomato plant [15].

It is found from the literature that the plate heat exchanger is widely used, having specifications suitable for the semiconductor plant achieved the demand of the production process towards temperature, not higher than 55 ℃. Many research articles [16]-[22] has made a discussion on the heat exchanger that can be used in the semiconductor plant, but still waiting for implementation. This paper attempts to fill this gap by implementing the heat energy recovery from air compressors using plate heat exchanger in the semiconductor plant. This paper has an objective in finding out the waste heat released from the semiconductor plant, utilized for generation of supply using hot water governing the production process replacingdiesel boiler based generation. In addition, adapting compressors are used for the exchange of heat to cold water to eliminate back pressure imparted to the main cooling system of compressors. Temperature controlling of the cold water can be easily regulated using intelligent controlling techniques by making continuous adjustments to the heating of air while waste heat can be used to provide heat energy to the cold water. An attempt is being made to achieve the thermal balance between the heat recovered and the heat needed on the regular basis, resulting in effective heat energy recovery with the water-cooled compressors. Plate heat exchangers offer a frugal way to capture heat from the rotary screw compressor and utilize it to obtain the hot waterused in diverse processes. Many heaters are now operating with ~85% efficiency or better, and thus compressor based heat recovery activities will result in relatively profitable annual energy savings. An important argument can also be made beyond energy savings corresponding to heat recovery activities offering a significant amount of benefits tothe environment. This substantial amount of energy savings thereby reduces the carbon footprint in a semiconductor plant, where policy making and regulations towards the energy use is becoming an important facet in Thailand.

The rest of the outline of the paper are written as follows: Section II provides a brief overview of different methodologies adopted in a semiconductor plant, including the clean dry air system, diesel boiler hot water generating, and heat integration by a plate heat exchanger with economic and environmental consideration. In Section III, numerical examples are discussed. Section IV highlights the result and discussion. Final Section is for the conclusion.

II. METHODOLOGY

A. Clean Dry Air System

Fig. 1 shows the basic flow diagram of air compressor based supply in the production process having input parameters as: the flow rates are 7,000–8,000 Cubic Feet per Minute (CFM), the temperature below 40 ℃ and air pressure more than 110 pounds per square inch (psi). The simple working module is explained as: (i) a large air compressor used for generating air supply with a flow rate of about 8,000 CFM, temperature of about 90 ℃ to 100 ℃, and air pressure of about 110 psi providing a continuous supply, (ii) a shell-and-tube type heat exchanger used for reducing the air temperature from 90-100 ℃ to below 40 ℃, using a heat exchanger with the cold water, (iii) a cooling tower used to perform heat energy exchangeby mixing the heating air at 90 ℃ to 100 ℃ with the cold water at 32 ℃ which becomes 38 ℃ and returns to the cooling tower for the evaporation at the ambient temperature, and hence, after an evaporation process, the pressure will drop from 45 psi to 40 psi which means it reduces by 5 psi, and (iv) an air tank with air capacity of around 1000 litersused for air storage. Now, output parameters have value as: the temperature is below 40 ℃, airflow rates are more than 7,800 CFM, and the air pressure is about 110 psi.

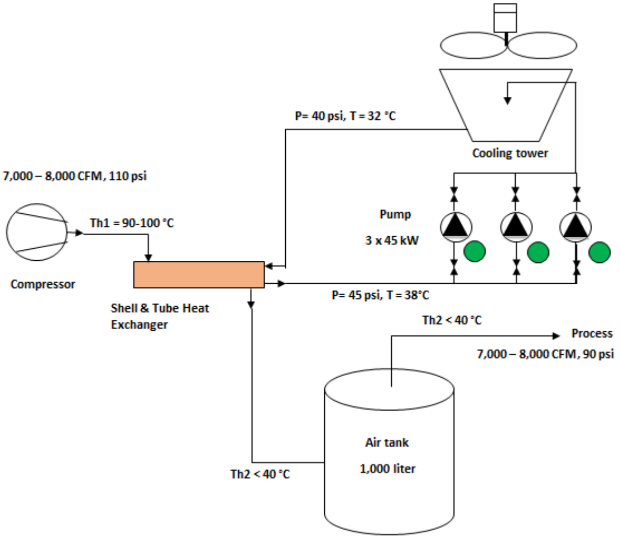

Figure 1. Existing schematic diagram of air compressor.

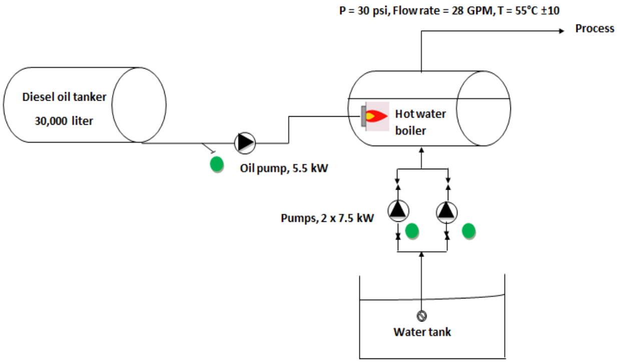

Figure 2. Existing schematic diagram of hot water boiler.

B. Diesel Boiler Hot Water Generating

Fig. 2 shows the basic flow diagram of hot water based supply in the production process for an interruption-free power supply, having constraints as: the flow rate is 28 Gallons per Minute (GPM), pressure is about 30 psi, and a temperature is about 55 ℃±10. The Reverse Osmosis (RO) with Deionized Water (DIW) is used for processing water and given to a diesel boiler for the generation of the heat supply. Diesel boiler transfersthe heatto the water from 30 ℃ and rises up to 55 ℃, resulting in the consumption of dieselaround 110 liters per day. The averagevalues of the energy and diesel consumption of the existing system are 46,200kWh per month and 3,373 liters, respectively.

C. Heat Integration by a Plate Heat Exchanger

1) Plate heat exchanger [23]

The corrugation on the plates provides the passage through the plates supporting each plate against adjacent one and enhances the turbulence, resulting in an efficient heat transfer as shown in Fig. 3 and Fig. 4. Fig. 3 shows the basic flow principle of a plate heat exchanger; Fig. 4 shows an integrated schematic diagram of the clean dry air system with the hot water generating systemused in heat energy recovery from the compressed air. It should be noted prior to implementation that the specification of the constraints remains unchanged for both water supply to the production process and air supply to the production process. The simple working module is explained as: (i) a plate heat exchanger is installed, which connects an inlet piping for the air compressor supply to achieve intelligent valve control, (ii) connects an outlet compressed air prior to the inlet air tanks, and (iii) Connection is established between an outlet water supply to the production process, and an intelligent temperature control with a backup heat pump followed by connecting inlet piping for the water supply. It is clear from the Fig. 1 and Fig. 2 that every single parameter related to supply and to the production process remains unchanged. One can neglect diesel boiler from this system.

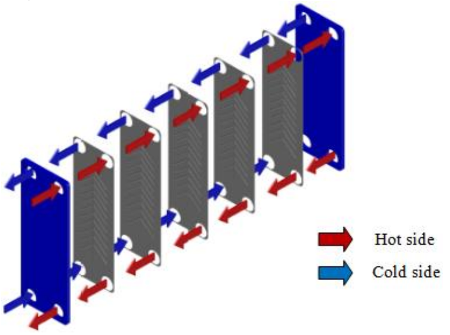

Figure 3. Flow principle of a plate heat exchanger.

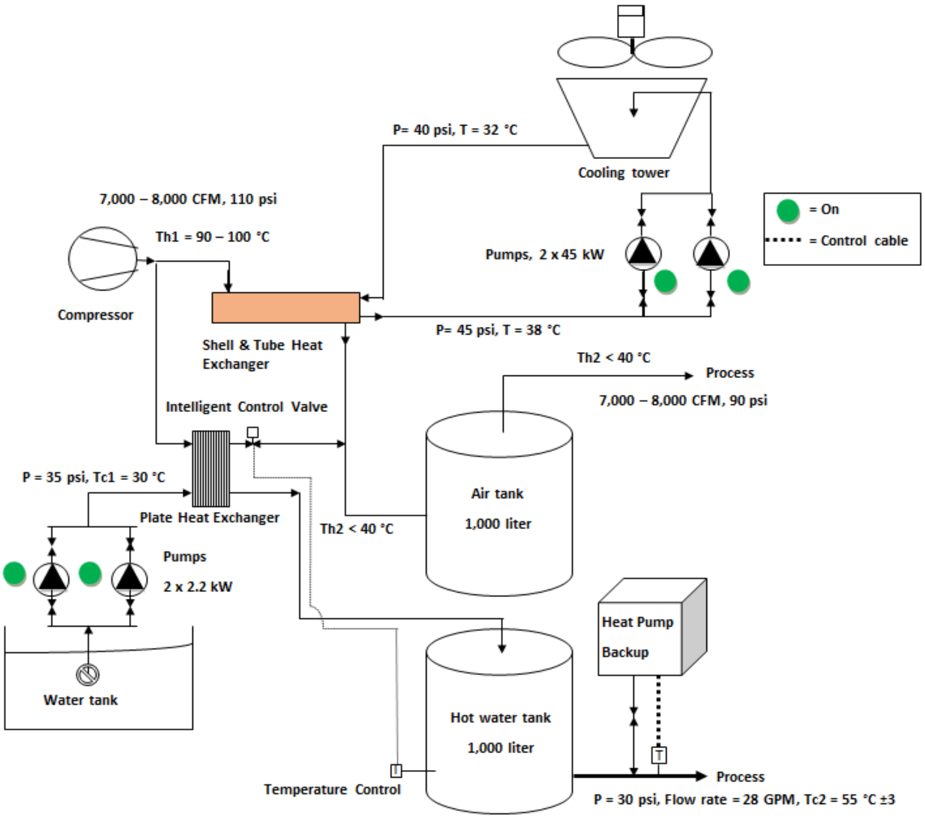

Figure 4. The proposed system.

Basic features of the plate heat exchanger used in this research, such as width, height and thickness, sizing of an inlet pipe and outlet pipe, heat exchange, maximum flow rate, maximum pressure, and material used, respectively based on the Alfa Laval T20 model as shown in Table I.

2) Heat transfer formulation

Various experimental parameters are selected for the formulation of heat transfer using PHE are an inlet and outlet temperature, pressure, and flow rate of hot air side and cold water side, respectively under standard unit as shown in Table II. All parameters are obtained by taking measurement standard tool based quality management system, calibrated in every six months.

TABLE I. GEOMETRIC CHARACTERISTICS OF PLATE TESTED IN THE PRESENT STUDY

Parameter	Value	Unit
Plate width	780	mm.
Sizing hot side inlet	200	mm.
Sizing cold side inlet	200	mm.
Plate thickness	0.5	mm.
Design temperature	180	℃
Maximum heat transfer surface	600	m^2
Plate high	2,145	mm.
Sizing hot side outlet	200	mm.
Sizing cold side outlet	200	mm.
Design pressure	150	psi
Maximum flow rate	225	Kg/s
Stainless steel (316) Thermal conductivity	16.5	w/m^2 k

TABLE II. EXPERIMENTAL PARAMETER DATA

Parameter	Hot air side	Cold water side	Unit
Temperature inlet	90	28	℃
Temperature outlet	<40*	55±10*	℃
Pressure input	110	30	psi
Flow rate	470	188	l/s

Remark: *It is parameter control if it out of range will be impacted to production shut down.

An outlet temperature of heat transfer fluid means the temperature values between an active portion of the heat side and the cold side. Heat transfer analysis of plate heat exchanger is defined by (1) where, Q is the heating load (W), U is an overall heattransfer coefficient (W/m^2 ℃), F is a correction factor [24], A_p is an effective plate heat transfer area (m^2), N is the number of channels, T is the temperature (℃), ΔT is the logarithmic mean temperaturedifference,and NTU is number of heat transfer units.

$$Q = U\ (N-1)\ A_P F \Delta T_{lm} \tag{1}$$

$$\Delta T_{lm} = \left(\Delta T_{in} - \Delta T_{out}\right) \Big/ \left(\ln\left(\Delta T_{in} / \Delta T_{out}\right)\right) \tag{2}$$

$$F = 1 - \left(0.0166(NTU)\right) \tag{3}$$

$$NTU = \left(UNA_P\right) \Big/ \left(mc_{min}\right) \tag{4}$$

Equation (4) and (5) are used to determine the transfer rate of heat transfer fluid in each side of PHE where, h is hot air side, c is cold water side, Q is the heat load(W), m is mass flow (kg/s), and Cis specific heat (J/kg ℃), and R is resistance.

$$Q_h = m_h C_h \left[T_{h,\ in} - T_{h,\ out}\right] \tag{5}$$

$$Q_c = m_c C_c \left[T_{c,\ out} - T_{c,\ in}\right] \tag{6}$$

$$R = m_c C_c / m_h C_h \tag{7}$$

$$\left(T_{h,\ in} - T_{c,\ out}\right) \Big/ \left(T_{h,\ out} - T_{c,\ in}\right) = E \tag{8}$$

$$E = \exp\left[\left(UA_p NF\right) \Big/ \left(m_c C_c\right) \times (R-1)\right] \tag{9}$$

The temperature of the hot air out and cold water out are:

$$T_{h,out} = \left[(1-R)T_{h,\ in} + (1-E)RT_{c,\ in}\right] \Big/ (1-RE) \tag{10}$$

$$T_{c,\ out} = T_{c,\ in} + \left(T_{h,\ in} - T_{h,\ out}\right) \Big/ R \tag{11}$$

3) *Payback period calculation*

Calculation of the payback period is defined as the amount of time required to recoverthe investment cost The Spasion(Thailand) limited [25] has criteria regarding the payback period corresponding to the investment made basically used to justify the project below 2 years.

$$\text{Payback Period} = \text{Investment} / \text{Annual Cash Cost Saving} < 2 \tag{12}$$

4) *CO_2 calculation*

The amount of air pollution emissions is calculated by the estimation of CO_2 emission stemming out from the semiconductor plant depending on energy usage. For this estimation task, the amount of energy consumed and CO_2 emission factor depending on fuel type should be known. Methodologies related to the CO_2 emissionsare described in [26] and represented by the (13) where, CO_2 Emission means the amount of CO_2 emission corresponding to the energy consumption, EF_{Fuel} means the coefficient of CO_2 emission depending on each fuel type, and FC_{Fuel} means the amount of utilization of eachfuel type.

$$CO_2\ \text{Emission} = \sum\left(EF_{Fuel} \times FC_{Fuel}\right) \tag{13}$$

5) *Control chart principle*

A control chart may be defined as a graphical method for evaluating whether a process in or out from the state of statistical control. It consists of a center line, Upper Control Limit (UCL), and Lower Control Limit (LCL). The purpose of the control chart is to achieve standardization for a process so that the management might strive to use an instrument to attain the desired target, and serves as a mean for making judgmentwhether the desired goal has been reached or not [27]. Where, χ is the central line, U_{CL} is the upper control limit, L_{CL} is the lower control limit, n is the number of variables, σ is the standard deviation.

$$\chi = \text{sum}(x) / n,\ n = 1, 2, 3............, n \tag{14}$$

$$U_{CL} = \chi + 3\sigma \tag{15}$$

$$L_{CL} = \chi - 3\sigma \tag{16}$$

This paper demonstrates the concept and application of temperature control charts in a semiconductor plant. The influence of this chart on quality improvement, adjust to optimal point control, and cost reduction is also observed.

III. NUMERICAL EXAMPLE

For the heat energy transfer calculation, the parameter of Alfa Laval T20FMG as follows; U_0= 2,547 W/m^2-K, Width = 0.78m, High = 2.175m, Gap = 0.005m, Thickness = 0.001m, N = 217, and A = $1.6731m^2$. On hot air side, m_h =470kg/s, $T_{h,in}$ = (90 + 273) = 363K, C_h = 723J/kg-K, $m_h c_h$ = (470 × 723) = 339,810W/K. On cold water side, m_c =187kg/s, $T_{c,in}$ = (28 + 273) = 301K, C_c = 4,200J/kg-K, $m_c c_c$= (187 × 4,200) = 785,400W/K. From (4), NTU = (2,547 × 207 × 1.6731) / 339,810 = 2.596.

From (3), (7), and (9), F = 0.957, R = 2.311, E = 4.093042, From (10), and (11), T_{h2} = 36.9 ℃, and T_{c2} = 50.9 ℃.

For the calculation of payback period, an investment is around 3,000,000 Baht and the gainobtained through cost saving is at: (i) the total electricity consumption reduces to 202,703 kWh per year, or about 750,000 Baht per year, (ii) the diesel oil consumptionreduces to 36,500 liters per year, or about 1,095,000 Baht, (iii) the repair and maintenance cost of boiler reduces to 180,000 Baht per year, and (iv) the payback period equals to 1.5 years as calculated from (12), respectively.

A significant amount of gain is obtained by reducing electricity consumption and diesel oil usage, respectively, used to perform the CO_2 conversion. Conversion takes place from the two separate systems to one single system to obtain these reductions. Using (13), CO_2 emissions equal to (202,703kWh × 0.542) + (36,500 liters × 2.68) kg CO_2 per year, i.e. 207,685kg CO_2 per year where, the conversion factor equals to 0.542 kg CO_2 saved for each kWh, 2.68kg CO_2 per saved foreach liter diesel fuel, exchange rate = 30 Baht per USD and 3.7 Baht per kWh, and diesel fuel = 30 Baht per liter.

The outlet temperature valueof the cold water must be reached to 55 ℃±10 for making a significant amount of improvement in the hot water temperature control chart. By using (14), (15), and (16), calculate the following values as: χ = 55 ℃, U_{CL} = 65 ℃, and L_{CL} = 45 ℃, this indicates that a wide range of temperature has to control. It is clear from the Fig. 5 that the temperature remains out of range time, thus, an improvement has to be achieved at this point. For an old system, UCL_{old}, 65 = 55 + 3σ i.e. σ = 3.33, and LCL_{old}, 45 = 55 + 3σ i.e. σ = -3.33. For the new system UCL_{new}, 58 = 55 + 3σ, i.e. σ = 1, and LCL_{new}, 52 = 55 – 3σ i.e. σ = 1, this facilitates to adjust the U_{CL} and L_{CL} from 55 ℃±10 to 55 ℃±3.

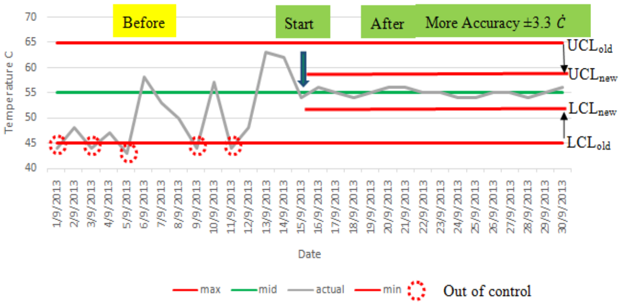

Figure. 5. Temperature new control charts control range.

IV. RESULT AND DISCUSSION

The potential benefits of this work found from the experiment are as follows: (i) increment in the stability of the overall system using an intelligent valve control by generating supply from the hot water in the production process. The temperature of the system has more accuracy within a range of ± 3 ℃, resulting in a better specification than an existing system having a control range of ±10 ℃ as shown in the Fig. 5, (ii) the electricity consumption reducesto 202,703kWh per year due to stopping of one big pump of the cooling water from 3 machines to 2 machines, thereby, reducingthe size of the supply pump, (iii) diesel fuel consumption reduces to 36,500 liters per year by stop using a diesel boiler, (iv) carbon emission content reduces to 207,685kg CO_2 per year by stop using diesel fuel supply to boilers, (v) repair and maintenance cost reducesto 180,000 Baht per year by stop using boiler as per the inspection of Thai regulation law enforcement, and (vi) increases reliability employing heat pump as the backup system, when air compressor machine shutdowns or in case of emergency failure, thus, providing an interruption-free supply to the production process from the heat pumps.

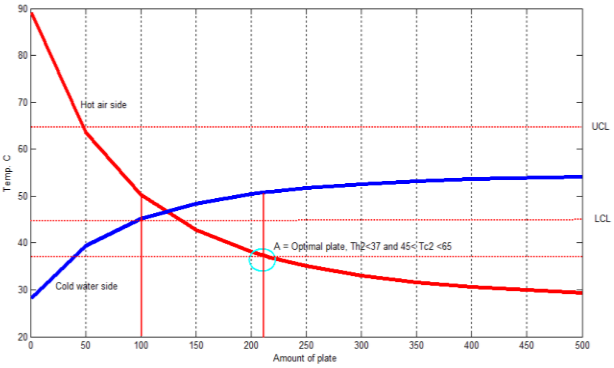

Figure 6. The optimal plate design.

The optimal amount of plate heat exchanger as shown in Fig. 6 has 217 plates because the outlet temperature ofair compressor is below 37 ℃ and the outlet temperature of the cold water is within the standard range 55 ℃±10 and after 217 plates onwards also, the outlet temperature of air compressor and the cold water, respectively remain unchanged. If plates lower than 217 are used, then the output temperature of air compressor becomes more than the standard range control, below 37 ℃. Considering the economic aspects, one should select 217 plates due to their low installation cost and all parameters are within a standard range.

This paper gives an overview of heat energy recovery (waste heat) from the air compressor using a plate heat exchanger in a semiconductor plant. One must collect allrelevant data and constraints related to existing systems and should perform an analytical study in terms of its strength, weakness, and feasibility as shown in Table III. In addition, one should meetarea owners to understand more clearly about the problems and can start finding solutions for the problem. Energy conservation can also be achieved by this principle of heat energy recovery and can be applied to hotels, hospitals or government agencies helping them to achieve cost saving. It will become a paradigm related to energy usage, leading a growth of the nation. In future, this can also become a good alternative to fuel. On the other hand, it also reduces the constructional cost of a power plant. The outlet temperature of the hot air side is around 36.9 ° Creduced from the inlet temperature, i.e. 90 ℃; however, it is within a standard range control at below 40 ℃. On the cold water side, the temperature increase from 28 ℃ to 50.9 ℃, and within standard range control at 55 ℃±10. An intelligent control valveis used to target the outlet temperature in a precise manner and adjust the flowrate of hot side temperature as desired.

TABLE III. FEASIBILITY STUDY RESULT OF TEMPERATURE OUTLET

Parameter	Hot air side	Cold water side	Unit
Temperature inlet	90-100	28	℃
Temperature outlet	36.9(<37)	50.9(55±10)	℃
Pressure input	110	30	psi
Flow rate	470	188	l/s

A comparative outcome between an existing system and the proposed system can be found in Table IV. To validate the system performance, the difference in the parameter valuesis observed by replacing the existing system with the proposed system. Considerable savings are achieved with the proposed system, cancelling out the need of the diesel oil for generating continuous supply for production process.

A plate heat exchanger is used in the proposed system to recover the waste heat energy into the system for generating the continuous or interruption-free supply the production process.

V. CONCLUSIONS

Compressed air processing generates the waste heat as the hot air that removes temperature by using shell and tube heat exchanger. Existing processing techniques did not able to provide anyheat energy recovery in the form of the waste heat. One has a potential to recover and apply the hot air waste heat exchanger with cold water by using plate heat exchanger. Case study indicates towards the energy and monetary savings of 202,703kWh per year, diesel oil 36,500 liters per year, carbon emission 207,685kg CO_2 per year, and 180,000 Baht per year, respectively, with the payback period of 1.5 years. A numerical analysis is performed using the mathematical tool to validate the proposed model. A comparison has performed between the analytical results and the obtained numerical data with actual data showing the significant potential benefits of this new initiative of using waste heat energy recovery, while the magnitude of energy and monetary savings will vary with throughput from utility to utility, the major portion of the savings are expected to come out from the hot water usage with the corresponding reduction in the use of purchased diesel oil. Although, the electricity savings from decreased cold water pumping, the cooling tower usage, and maintenance cost by using the heat energy recovery is a small fraction of the total energy savings, relatively high cost of electricity relative to diesel oil makes these savings as a major account of the total monetary savings. Rapid increase in energy pricing structure is becoming a major concern, so one has to gain some economic benefits and the compressed air based heat energy recovery is surely bringing a ray of hope, but total energy and monetary benefits are largely dependent on the properties of the type of heat exchanger used and the temperature difference between the compressed air and cold water, respectively. Demonstrated potential for compressed airbased heat energy recovery in the hot break motivate to study the implications and intricacies as a future work for ensuring the paste quality when a two-stage hot break using recovered waste heat is employed and application of the control chart principle to another variable control range improvement is being performed.

TABLE IV. COMPARISON BETWEEN THE EXISTING SYSTEM AND THE PROPOSED SYSTEM

Description	Existing system	Proposed system
General features	Require two separate systems for the hot water and the cold water using diesel oil and pump	Two separate systems are integrated together to make a single integrated system using a plate heat exchanger
Numbers of pumps required	6	4
Size of the pumps	2×7.5 kW (Hot water)	2×2.2 kW (Hot water)
	1×5.5 kW (Oil pump)	Not required
	3×45 kW (Cold water)	2×45 kW (Cold water)
Output temperature variation,Tc_2	±10 ℃	±3 ℃
Precision tool	Not applicable	Intelligent control valve
Cost effectiveness	Need diesel oil of 36,500 liters per year	No need of diesel oil

ACKNOWLEDGEMENTS

The valuable support received from the Faculty of Engineering, Thammasat University and the Spansion (Thailand) are greatly appreciated and acknowledged.

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