In the automotive industry, the demand for thermal energy is approximately 70% of the total power consumption of the automobile manufacturing process. If the flue gases emitted during the manufacturing process is not recycled or reused effectively, the environment will be impacted. Therefore, the United Nations Intergovernmental Panel on Climate Change (IPCC) established plans in 2014 intending to reduce the Greenhouse Gas (GHG) emissions especially CO$_2$ emission by 40%-70% in 2050 from 2010. Previously, a change of innovative energy conservation technologies could promote a more effective utilization of energy.

The waste heat of industries in Taiwan is approximately 9% of the total energy. The Ministry of Economic Affairs, Taiwan, has been encouraging private enterprises to conduct research and development on waste heat recovery and applications since 2011. Previous research focused on high-temperature waste heat recovery of devices for industries such as steel, chemical engineering and electronics. Currently, the related cases of low-temperature waste heat and waste cold recovery have been employed to other
industries. Therefore, this study intends to extend the low-temperature waste heat recovery technology to the automobile painting factory.

Thence, this study uses the specific practices of regenerative thermal oxidation to consider its operating temperature range from 750°C to 820°C. Such high temperatures can incinerate Volatile Organic Compounds (VOCs) in the oven of the painting factory, to reduce environmental pollution. In view of the air volume range of emitted flue gases in RTO is range from 700 Nm³/min to 1000 Nm³/min and its temperature range from 150°C to 180°C. The heat exchange design of flue gases-to-water economizer (ECO) can be used for waste heat recovery. In fact, there were two common drawbacks in the waste heat recovery of the automotive industry. First, Energy loss occurs in the delivery. The deliver process was that the hot water heated from waste heat recovery was feed to boiler, and then the steam produced by the combustion of the natural gas was delivered to the manufacturing process. Second, the lower the thermal conduction performance of the waste heat recovery, resulted from a single shift production in the automobile workshop, that was created by thermal resistance of frequent thermal expansion and contraction effect using the embedded or extruded type heat pipes.

The purpose of this study aims to improve the drawbacks of the conventional waste heat recovery of the automotive industry. First, the hot water obtained from the innovative heat recovery system is directly delivered to the pretreatment tank of painting shop in order to reduce steam pipe transport loss. This reduces the fuel usage of the steam boiler and achieves the effects of energy conservation and carbon reduction. Second, the design of high-frequency welding segment technology provides the solution to overcome the problem of lower the thermal conduction performance. Moreover, another feature of innovative recovery technology of waste heat is to extract heat close to an acid dew point, which results in energy efficiency 69% higher than conventional design.

This paper is organized as follows. The use of high frequency welding segment technology for RTO waste heat recovery and a review of the factors affecting waste heat recovery are introduced in the next section. In section 3, features of innovative RTO waste heat recovery system is proposed in detail. In section 4, the case study of automobile factory in Taiwan is conducted to illustrate the innovative waste heat recovery system and the cost-benefit analysis. The discussion on the affect factors of waste heat recovery are further investigated in section 5. Concluding remarks are addressed at the end of article.

2 | LITERATURE REVIEW

Based on the concept of sustainability and energy conservation, automobile factories should devote to solving the problem of air pollution caused by VOCs emission. Past cases show that the methods of using activated carbon oxidation, catalytic converter and regenerative thermal oxidizer (RTO) can comply with the environmental protection requirements. The RTO method is extensively adopted to provide a reliable solution in automobile industry. For achieving the energy conservation effect, in recent years, most of factories in the automobile industry installed a flue gases ECO waste heat recovery devices to existing equipment to reduce the natural gas cost.

2.1 | RTO waste heat recovery technology

In RTO technology, an oxidation furnace for regenerative combustion is applied, which produces high temperature from 750°C to 820°C to incinerate VOCs in the flue gases, for reaching emission standard. In this study, the waste heat recovery system is installed on the RTO with three tanks. The operation of the flue gases treatment uses two tanks for air intake and one tank for air discharge. The inlet and outlet of each tank are switched every 90 seconds, and the switching time of the tank is set according to the structure and the flow composition of the flue gases flow. While the switching time shorter, the heat has higher conversion efficiency. However, the rule of retaining the flue gases for staying at least one-second must be followed in order to eliminate the harmful VOCs in accord to regulations of air pollution protection. The tanks are filled with thermal insulating blocks of the heat exchange media; which material is generally saddle type heat-storage ceramic material. The ceramic material in the tank is heated up to approximately 650°C when the waste heat of the flue gases containing VOCs enters the inlet into the tank. The burners further increase the temperature to range from 750°C to 820°C to incinerate the toxic gases convert it as clean air before being discharged from the outlet. After, the flue gases 820 °C at the top flowing through the thermal storage ceramic material then decline to about 160°C at the bottom as shown in Figure 1.

The operating cost of flue gases treatment depends on the usage of fuel, which more consumption incurs higher operating cost and greater greenhouse gas emission. In addition, the greater treatment of the flue gases emission results in higher annual air pollution fee. Therefore, the RTO renders the economical solution. In this study, ECO is installed in front of an induced draft fan to perform the waste heat recovery, which heat recovery is delivered to the painting shop pretreatment process.

2.2 | Application of high frequency heat exchanger

In operation of the automobile manufacturing process, the flue gases temperature of RTO exhausted can reach the range from 150°C to 180°C, but drop to the range of 80°C to 90°C.
in next day after the furnace is turned off, which results in a frequent thermal cycling stress. The enhanced device with thermally conductive fin on flue gases side of ECO is loaded with frequent thermal expansion and contraction effect resulted from the thermal cycling. The disadvantage of embedded type heat pipe is that may be easily loosened from the fin. On the another hand, and extruded type of fin heat pipe may result in a gap with fin tubes that easily create source of thermal resistance which lowers the thermal conduction performance in whole. The heat extraction capacity of the flue on both embedded type and extruded type may decrease with time, which shortens rapidly the product life cycle. In order to overcome these drawbacks, the high frequency welding segment ECO is proposed.

This high frequency welding segment ECO is made by fin tubes which are installed with high frequency welding segment method. The higher conversion efficiency gains from the creation of thermal turbulence by increasing heated surface on welding segmented fins as shown in Figure 2. For improving the connectivity of fin tubes on the ECO, the priority is supreme aluminum fin tubes, serrated fin tubes, solid fin tubes according.10

2.3 The factors affecting waste heat recovery

Based on the flue gases conditions and heat extraction requirement of the RTO furnace, the design of the low-temperature flue gases recovery and utilization have applied to the automobile painting shop. The best design criteria for extraction from the waste heat are heat exchange cost, ECO weight and performance heat transfer.11 The system design of heating and extraction adopts flue gases to water heat exchange, in which the hot water system is a closed loop cycle. The heating capacity (kW) depends on the circulating water volume (M³/h) and the temperature difference ΔT after passing through the heat exchanger.12 The variability of the production quantity and seasonal weather temperature affect the amount of heat extraction in the flue gases.13

3 FEATURES OF INNOVATIVE RTO WASTE HEAT RECOVERY SYSTEM

3.1 Pretreatment operation in painting shop

In the pretreatment workflow of the painting shop, hot water used to clean up the grease on body before the body enters the painting station for spray-painting. Its workflow is described as follows: warm water rinsing tank, hot rinsing tank and degreasing tank are prepared. In the workflow, the boiler uses natural gas to produce steam with pressure of 7 kg/cm². The steam is provided for heating of each tank, which may be direct or indirect heating. The water tank adopts the direct heating to achieve higher heat conduction efficiency as shown in Figure 3, and the indirect
heating typically uses frame type heat exchanger on chemical solution tank, in order to keep same the concentration of the chemical solution.

The thermal energy of pretreatment tanks required temperature range are from 45°C to 55°C as show in Table 1.

3.2 Utilization of RTO waste heat recovery

The innovative design of the RTO waste heat recovery system uses closed loop circulating hot water for heating and extraction. After the circulating hot water extract heat from the flue gases, it is sent to pretreatment tank at painting shop for indirect heat exchange. The hot water after exchange is returned to the heat-extraction end of the ECO. The design of the directly sent to the pretreatment tank for heating, which can avoid steam loss in boiler steam pipes.14

The required heat energy of each tank depends on not only the production capacity but also the average weather temperature. The heat extraction from RTO is unable to provide sufficient heat energy in the winter at weather temperature average 16°C at Taiwan, which needs compensate with steam from boiler. However, the heat can be reduced in summer, at average weather temperature 29°C, which result in higher exhaust temperature.13 To estimation, the heat energy required for each tank, the heat equilibrium analysis is performed as shown in Figure 4.

| Tank name       | Volume (KL) | Demand temperature (°C) |
|-----------------|-------------|-------------------------|
| Warm water rinsing | 3           | 45-50                   |
| Hot rinsing     | 85          | 50-55                   |
| Degreasing      | 120         | 50-55                   |
| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Average temperature (°C) | 15.0 | 14.8 | 18.3 | 22.7 | 25.5 | 28.8 | 31.5 | 30.4 | 30.6 | 24.8 | 21.2 | 15.2 |
| Q1 Stir the heat | | | | | | | | | | | | |
| Warm water | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 | 4300 |
| Hot rinsing | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 | 16 125 |
| Degrease | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 | 14 190 |
| Q2 Car body with heat | | | | | | | | | | | | |
| Warm water | 91 296 | 91 905 | 81 253 | 67 955 | 59 342 | 49 300 | 41 083 | 44 431 | 43 822 | 61 473 | 72 428 | 90 657 |
| Hot rinsing | 106 512 | 107 121 | 96 469 | 83 171 | 74 558 | 64 516 | 56 299 | 59 647 | 59 038 | 76 689 | 87 644 | 105 873 |
| Degrease | 112 598 | 113 207 | 102 556 | 89 257 | 80 645 | 70 602 | 62 386 | 65 733 | 65 124 | 82 775 | 93 731 | 111 959 |
| Q3 Static radiation heat loss | | | | | | | | | | | | |
| Warm water | 7050 | 7097 | 6275 | 5248 | 4583 | 3807 | 3173 | 3431 | 3384 | 4747 | 5593 | 7001 |
| Hot rinsing | 82 250 | 82 720 | 74 495 | 64 226 | 57 575 | 49 820 | 43 475 | 46 060 | 45 590 | 59 220 | 67 680 | 81 757 |
| Degrease | 115 973 | 116 635 | 105 038 | 90 558 | 81 181 | 70 246 | 61 300 | 64 945 | 64 282 | 83 500 | 95 429 | 115 277 |
| Q4 Dynamic spray thermal loss | | | | | | | | | | | | |
| Warm water | 90 000 | 90 600 | 80 100 | 66 990 | 58 500 | 48 600 | 40 500 | 43 800 | 43 200 | 60 600 | 71 400 | 89 370 |
| Hot rinsing | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 | 200 000 |
| Degrease | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 | 250 000 |
| QT1 Total calorie needs | Warm water | −184 046 | −185 302 | −163 328 | −135 892 | −118 125 | −97 407 | −80 456 | −87 362 | −86 106 | −122 520 | −145 121 | −182 728 |
| QT2 Total calorie needs | Hot rinsing | −372 637 | −373 716 | −354 839 | −331 271 | −316 008 | −298 211 | −283 649 | −289 582 | −288 503 | −319 784 | −339 199 | −371 504 |
| QT3 Total calorie needs | Degrease | −458 295 | −459 566 | −437 317 | −409 539 | −391 549 | −370 572 | −353 409 | −360 401 | −359 130 | −395 999 | −418 883 | −456 960 |
| Total pretreatment tank heat (kW) | | | | | | | | | | | | |
| | −1180 | −1184 | −1111 | −1019 | −960 | −891 | −834 | −857 | −853 | −975 | −1050 | −1176 |

Q1 = 860 × J × 0.5 = 4300 Kcal/h; Q2 = units/h × kg/unit × 0.12 × (45°C−Ambient Temperature); Q3 = [(S1 × 20 kcal/M² h.°C) + (S2 × 5 kcal/M² h.°C)] × (45°C−Ambient Temperature); Q4 = 3 Ton/h × Specific heat × (45°C-Reflow Temperature Kcal/h) Kcal/h; QT1 (Warm water)Kcal/h = Q1−(Q2 + Q3 + Q4); QT2 (Hot rinsing)Kcal/h = Q1−(Q2 + Q3 + Q4); QT3(Degrease)Kcal/h = Q1−(Q2 + Q3 + Q4).
The monthly heat energy required of warm water tank, hot rinsing tank and degreasing tank is listed in Table 2. The Table 2 shows that the monthly of the three tanks total heat demand from January to December, the minimum heat demand of 834 kW occurred in the summer (Jul.) and the maximum heat demand of 1184 kW occurred in the winter (Jan.).

The flue gases waste heat extracted from the RTO furnace is supplied to the pretreatment tank as shown in Figure 5. The entire system design of the waste heat recovery is divided into 4 sub-systems; (a) flue waste heat extraction system; (b) closed hot water circulation supply system; (c) pretreatment heat supply system; (d) control system. In the meantime, a controller is developed to adapt the flue gases temperature higher than the acid dew point after heat extraction, which prevent the induced draft fan and the wall of the flue from being corroded or damaged. Another function of controller is distributing the heat to each tank for keeping set temperature within the required range.

### 3.3 | Design of high frequency economizer

As the ECO design adopts high frequency welding with heat extraction close to an acid dew point, the performance of this design is much higher than conventional design. An innovative ECO is designed according to the conditions of RTO furnace operation and effect of the thermal expansion and contraction. Therefore, ECO features with anti-corrosion of thermally fins and heat extraction close to acid dew-point temperature.

### 3.3.1 | Anti-corrosion of thermally fins

For the purpose of anti-corrosion, the ECO of flue heat extraction adopts heat pipe made of SUS 304 stainless steel tubes with pure aluminum fins tubes to provide anti-corrosion resistance. Since aluminum has strong chemical property, it may be reflecting with different acids, alkalis and oxygen in the atmosphere to form a layer of extremely dense oxide film. Although this film is only 20 μm thick, it is very dense and hard. The aluminum is exposed to the atmosphere will not corrode as long as the aforementioned film is not damaged. The higher the purity of aluminum is the better corrosion resistance. Therefore, the aluminum fin of this study is made of pure aluminum material (No. 1100), which better corrosion resistance. In addition, the structural strength at the joint of the aluminum fin and the stainless-steel heat pipe combined with the high frequency welding segment is greatly enhanced. It results in the subsequent maintenance can bear washing and...

### Table 3 | Waste heat analysis

| Ingredient | Molar rate | Thermal units | value |
|------------|------------|---------------|-------|
| CO₂        | 0.6%       | kg/m³         | 1.27  |
| O₂         | 20.0%      | kg/s          | 15.87 |
| H₂O        | 4.4%       | kJ/kg°C @160°C | 505.34 |
| N₂         | 75%        | kJ/kg°C @112°C | 453.23 |

Heat recovery, kW 792

The flue gases volume to 770 Nm³/min.
rinsing with high-pressure water columns without being easily damaged, twisted or deformed. Similarly, the aluminum oxide film on the aluminum fin is also well-maintained to guarantee the performance of its corrosion resistance. Since the high frequency welding segment directly melts the aluminum fin, it continuously connects the aluminum fin to the stainless-steel heat pipe. When the ambient temperature is changed substantially, the fins and the heat pipes are still connected very well to maintain the performance of the heat exchanger and extend the product life for long-term operation.  

3.3.2 Heat extraction close to acid dew-point

An anti-corrosive material is used to decrease the temperature difference with the acid dew point and improve the benefit of heat recovery of the flue gases waste heat. The lower the flue gases temperature after the heat extraction, the more of the recovered heat energy. However, it is still necessary to take the acid dew-point into consideration to prevent an excessively low flue gases temperature or corrode the downstream flue or chimney. Data of the discharged flue gases of the RTO furnace is revealed. The concentration of SO\textsubscript{x} is 2 ppm, and the volume percentage of H\textsubscript{2}O is 3.8 to 4.4%, and the main composition of general SO\textsubscript{x} is SO\textsubscript{2}, wherein a port of the SO\textsubscript{2} is converted into SO\textsubscript{3}. After SO\textsubscript{3} is combined with H\textsubscript{2}O, then H\textsubscript{2}SO\textsubscript{4} is produced. When the temperature is lower than the acid dew point, H\textsubscript{2}SO\textsubscript{4} will be attached onto tube wall of the flue gases to corrode the flue. The acid dew point is affected by the content of SO\textsubscript{3} and H\textsubscript{2}O. The higher the content, the higher the acid dew point, since detected data of the flue gases is not measured particularly based on the percentage of SO\textsubscript{2} and SO\textsubscript{3}, the acid dew point can be derived by \(\text{SO}_3/(\text{SO}_2 + \text{SO}_3) = 10\% \text{ to } 30\%\). In other words, the content of SO\textsubscript{3} is 0.2

| Items                        | Heat recovery method | Differences value |
|------------------------------|----------------------|-------------------|
|                              | Innovative | Conventional |                  |
| Flue gases inlet temperature (°C) | 160        | 160           | 0                |
| Flue gases outlet temperature (°C) | 112.4      | 130.5         | −18.1            |
| Acid dew point temperature (°C) | 100.5      | 100.5         | 0                |
| Flue gases outlet temperature and acid dew point temperature difference (°C) | 11.9       | 30            | −18.1            |
| Heat recovery capacity (kW)   | 792        | 470           | 322              |
to 0.6 ppm. A flue gases SO\textsubscript{x} acid dew point calculator is used to calculate the acid dew point temperature of the flue gases, which is found to be 92.3°C to 100.5°C, so the acid dew point temperature is set to be 100.5°C. The flue gases is increased to supply heat and drop the flue gases temperature to 112°C, which is 11.5°C higher than the acid dew-point temperature after the heat extraction, and smaller difference in temperature may be reserved to ensure operational safety.

### CASE STUDY

Company C was founded in June 1969 at the Taiwan, covers an area of 201,051 square meters and has an annual production workday approximately 240 days. Initially vehicle production was at a rate of 300 vehicles per month, but thanks to rapid growth, and the development of an advanced painting facility, the factory single-shift maximum production

| Month | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|-------|------|------|------|------|------|------|
| Jan   | NGasc | 224,665 | 254,160 | 120,071 | 127,749 | 133,979 | 123,062 |
|       | QProd | 4,889 | 5,433 | 3,619 | 3,678 | 4,122 | 3,976 |
|       | ATemp | 16.1 | 12.8 | 15.2 | 20.9 | 15.0 | 16.1 |
| Feb   | NGasc | 96,461 | 158,215 | 127,411 | 62,802 | 109,589 | 79,792 |
|       | QProd | 3,073 | 3,560 | 4,126 | 2,200 | 2,844 | 2,457 |
|       | ATemp | 18.6 | 15.4 | 16.0 | 18.1 | 14.8 | 15.2 |
| Mar   | NGasc | 140,862 | 233,591 | 120,715 | 85,141 | 104,121 | 90,884 |
|       | QProd | 4,402 | 5,910 | 5,016 | 3,483 | 3,480 | 4,155 |
|       | ATemp | 18.2 | 15.6 | 18.3 | 24.7 | 18.3 | 17.5 |
| Apr   | NGasc | 101,279 | 75,985 | 50,815 | 55,027 | 61,657 | 54,303 |
|       | QProd | 3,937 | 4,753 | 4,069 | 3,274 | 3,756 | 3,884 |
|       | ATemp | 21.0 | 22.6 | 24.1 | 25.7 | 22.6 | 18.2 |
| May   | NGasc | 61,852 | 54,744 | 38,765 | 37,375 | 49,149 | 33,911 |
|       | QProd | 4,676 | 5,599 | 4,957 | 4,156 | 4,563 | 4,275 |
|       | ATemp | 25.7 | 25.2 | 26.5 | 26.9 | 25.5 | 26.1 |
| Jun   | NGasc | 46,123 | 38,950 | 33,046 | 24,774 | 36,529 | 21,163 |
|       | QProd | 4,742 | 5,217 | 4,862 | 3,588 | 3,967 | 4,004 |
|       | ATemp | 27.3 | 30.4 | 28.6 | 29.9 | 28.8 | 31.0 |
| Jul   | NGasc | 34,002 | 40,015 | 30,354 | 27,484 | 27,727 | 27,171 |
|       | QProd | 4,904 | 5,835 | 5,245 | 4,330 | 4,272 | 4,211 |
|       | ATemp | 31.1 | 30.6 | 31.4 | 31.5 | 31.5 | 31.1 |
| Aug   | NGasc | 23,507 | 26,919 | 26,013 | 22,295 | 16,772 | 15,707 |
|       | QProd | 2,617 | 3,747 | 4,013 | 2,670 | 2,210 | 2,118 |
|       | ATemp | 31.3 | 30.6 | 31.4 | 30.4 | 30.4 | 29.5 |
| Sep   | NGasc | 35,464 | 39,145 | 28,014 | 29,267 | 26,963 | 29,498 |
|       | QProd | 3,737 | 4,758 | 4,163 | 3,248 | 3,254 | 3,648 |
|       | ATemp | 29.0 | 28.3 | 27.5 | 27.7 | 30.6 | 27.7 |
| Oct   | NGasc | 72,327 | 48,908 | 49,116 | 47,310 | 42,728 | 40,970 |
|       | QProd | 4,628 | 4,055 | 4,559 | 3,749 | 4,098 | 4,246 |
|       | ATemp | 24.0 | 24.3 | 24.2 | 23.95 | 25.0 | 24.3 |
| Nov   | NGasc | 117,016 | 66,931 | 70,392 | 74,690 | 59,531 | 53,266 |
|       | QProd | 5,067 | 5,078 | 4,615 | 3,641 | 4,025 | 3,234 |
|       | ATemp | 20.4 | 22.8 | 20.3 | 20.9 | 21.2 | 22.6 |
| Dec   | NGasc | 205,864 | 156,723 | 107,165 | 144,658 | 137,876 | 98,676 |
|       | QProd | 5,077 | 5,740 | 4,291 | 4,613 | 4,234 | 3,568 |
|       | ATemp | 16.8 | 16.0 | 17.1 | 15.55 | 15.21 | 17.51 |

ATemp, average weather temperature (°C); NGasc, Natural gas consumption (M\textsuperscript{3}); QProd, quantity of production (Cars).
capacity of 60 000 vehicles in 2017. They have been awarded numerous accolades for exemplary working conditions in their manufacturing plants, that have number of employees 2024 and capital USD 461 million.

This study takes the automotive industry company C as an example. The annual energy consumption of the company is 25 million kilowatts of electricity and 2 million cubic meters of natural gas. The energy policy of the case company follows three principles, which applied to the design, manufacture, sale, logistics management, and others, including the energy conservation, carbon reduction, and low power consumption and the sustainable environment. In addition, the company reviews the performance of energy conservation every year to devote on carrying out social responsibility by minimizing any harm to the community and environment for achieving the life of high-quality. In recently, company C has more actively corporate with the government in energy transformation policy to develop renewable energy and waste heat recovery technologies.

4.1 | Estimation of RTO waste heat recovery

4.1.1 | RTO flue gases condition

For the flue gases composition and emission in the estimation of the RTO waste heat recovery which sets the air volume to 770 Nm³/min. The molar volume ratio and weight of each component of in the flue gases are estimated and the heat property of each gases is used to obtain the enthalpy difference of the flue gases before and after the heat extraction, and the estimated flue gases may extract heat. The flue gases conditions are described as below.

- Emission of flue gases: 770 Nm³/min (1 atmospheric pressure, 20°C).
- Composition of flue gases: CO₂ (0.6%), O₂ (20%), H₂O (3.92% to 4.40%) and N₂ (75% to 75.48%).
- The flue gases temperature of before and after heat extraction: 160°C/112°C.

The extraction flue gases waste heat at different combinations of air volume and outlet temperature can refer Figure 10A–D. From the above measure data, according to the 770 Nm³/min green curve of Figure 10C, the total heat extraction is about 792 kW from 160°C to 112°C.

4.1.2 | Computation of heat extraction

The flow of flue gases is listed according to the composition of the exhaust flue, the heat property and the extracted heat are listed in Table 3. If the heat dissipation resulted from hot water circulation and heat exchange is 10%, the estimates of the heat extraction is 712 kW (792 kW × 90%).

The structure and operating principle of the waste heat recovery system as shown in Figure 6, and an ECO acts as system core. Under the condition of operating the ECO at a designed point, the overall heat transfer coefficient (K) is 36.8 W/m²K, the heat exchange area (A) is designed to be 390 m², and the relationship between heat transfer quantity (Q) and the cold- and hot-end conditions is represented by Equation (1):

\[ Q = K \times A \times \text{LMTD} = M_w \times C_p \times (T_4 - T_3)/0.9 \]  

where LMTD is the log mean temperature difference of the flue gases side and the water side, Mw is the mass flow rate of water, Cp is the specific heat of water, and T4 and T3 are the temperatures of the water outlet and inlet respectively. Since the thermal resistance is situated at the flue gases side, the air volume of the flue gases affects the value of K substantially. The larger the flue gases volume, the higher the value of K, and the larger the obtainable heat energy. If the heat energy required by the manufacturing process drops and the flue gases heat extraction requirement drops, then it will be necessary to control the proportional valve (MV-5) to limit and reduce the flow of hot water entering the ECO, so as to reduce the amount of heat extracted (Q). If the flue gases volume remains unchanged, but the flue gases temperature rises from 160°C to 180°C, then the LMTD of the ECO will be increased accordingly. Both the overall amount of heat extracted and T4 will also increase at the same time, and the energy conservation efficiency will be more significant.

4.2 | Performance

4.2.1 | Comparison on the range of waste heat extraction

As a result of actual verification, the recovery of low-temperature flue gases waste heat from RTO furnaces can be applied to the on-site thermal process. Since the conventional flue gases heat extraction technology generally sets the temperature after the heat extraction 30°C to 50°C higher than the acid dew point temperature, that is the flue gases temperature drops to 130.5°C, the extractive heat is 470 kW. The innovative system uses high-frequency welding aluminum fin tubes, the design is higher than the acid dew point 10°C to 20°C, which results in is 792 kW with having the performance 69% higher than conventional heat recovery as shown in Table 4.

4.2.2 | The benchmarking method

The benchmarking method of the improvement energy efficiency is primarily measured by evaluating
flue gases waste heat recovery performance by instrumental measurement or controller record, analyzing and usage the natural gas consumption as the baseline, as well as computation and usage the flue gases waste heat recovery amount as a reference for energy conservation. Make energy consumption baselines, its collect data as follows; Monthly natural gas consumption of production quantity and weather temperature are taken into consideration. The comparison of natural gas consumption per (unit) and weather temperature per (°C) are used as a reference for follow-up natural gas consumption. Related fuel consumption standard variables such as production quantity and average weather temperature are recorded one by one to facilitate establishment of the energy baseline. Therefore, linear regression model is proposed to investigated.

The monthly data of gas consumption, quantity of production and weather temperature from 2011 to 2015 as show in the Table 5 are employed to establish the energy baseline.

Estimated result of the energy baseline is given by the Equation (2).

\[
E(Y) = 189223.9 + 60.7X_1 - 17257.1X_2 - 2.2(X_1 X_2) + 0.001(X_1^2) + 402(X_2^2)
\]

\[\text{Adjusted } R^2 = 0.87. \text{ The } t\text{-value is given in parentheses } *, \text{ indicates } P\text{-value } < 0.05. \text{ Where, } E(Y) \text{ is average of the natural gas consumption (M}_3\text{), } X_1 \text{ is the quantity of production (cars), and } X_2 \text{ is the average weather temperature (°C). The response surface of natural gas consumption on production and weather temperature is as shown in Figure 7.}

This study uses energy baselines to forecast the monthly natural gas consumption for 2016, and compares the actual natural gas usage with the innovative waste heat recovery of method to calculate the total energy conservation. Total of energy conservation in 2016 is 228.7 kiloliters oil equivalent (KLOE) which is equivalent to reducing 483.5 tons of CO2 each year as shown in Table 6. It reveals that after the adoption of the innovative waste heat recovery system not only 257.2 KM3 of natural gas (30%) can be conserved, as shown in Figure 8, but also reduce the cost of natural gas pretreatment fuel and greenhouse gas emissions.

4.2.3 | Cost benefit evaluations of the innovative system

The RTO waste heat recovery equipment includes an ECO construction, control panel, hot water circulation system,
pipeline reconstruction, control panel, electromechanical system design, heat exchanger installation, flow and pressure detector, etc. The total investment amount is approximately USD 233 000. The payback year is 2.8 years, since employed the innovative waste heat recovery system, for the annual gas conservation amount is about 254 273M³. The price of natural gas is variable. Assuming that the unit price is USD 0.31/M³ and the annual benefit will be about USD 80 000. The annual cost benefit shift is shown in Figure 9.
5 | DISCUSSION

The waste heat extraction of the innovative system is affected by air volume and temperature in the flue gases. The design of flue gases allows air volume with range from 700 NM³/min to 1000 NM³/min. The temperature of flue gases may have a variable range from 150°C to 180°C. The extraction flue gases waste heat at different combinations of air volume and outlet temperature can refer to Figure 10.A–D.

This study shows that when the flue gases outlet temperature is 150°C, 160°C, 170°C and 180°C, the air volume varies within the range of 700 Nm³/min to 1000 Nm³/min. It shows the relationship between the outlet temperature after the flue gases heat extraction and the available heat energy. The flue gases extraction waste heat ($Q_g$) can be estimated according to the following Equation (3).

\[ Q_g = \frac{V_g}{60} \times (h_{gi} - h_{go}). \]  

where, $Q_g$ is the flue gases extraction waste heat (in unit of kW). $V_g$ is the air volume (in unit of M³/min) which is function of temperature. $h_{gi}$ and $h_{go}$ are enthalpies (in unit of kJ/kg) of the flue gases at the inlet and outlet of the ECO respectively, which is function of temperature. Enthalpies are related to temperature function as show in Figure 11.

For example, if the flue gases 770 NM³/min enthalpy ($h_{in}$) at 160°C is 505.34 kJ/kg, and the 112°C flue gases enthalpy ($h_{out}$) is 453.23 kJ/kg. The formula for heat extraction is as follows.

\[ Q = \frac{V (\text{Nm}^3/\text{s}) \times \rho (\text{kg/m}^3) \times (h_{in} - h_{out})}{60 \times \frac{\text{min}}{s}} = 792\text{kW} \]

6 | CONCLUSION

The proposed innovation system of waste heat recovery has actually achieved the dual goals of energy conservation and environmental friendliness in company C. There are two features in the innovative waste heat recovery system that one is the high frequency welding segment technology is used close to the acid dew point, another is the hot water is taken from the site directly for eliminating the loss of steam delivery. In addition, material selection of (such as pure aluminum material No. 1100) and high-frequency welding segment technology are the key factors achieve heat extraction close to the acid dew point. High-frequency welding technology used in low-temperature waste heat recovery can be extended to other industries such as hot water boilers.

In the past, steam boilers provided thermal energy for process in the automotive industry. In recent years, in order to improve the energy efficiency, employ the hot water boiler replace steam boiler to provide heat for pretreatment tanks in the automobile painting shop. The innovative RTO waste heat recovery can be widely used in the field of hot water boilers and pursue higher energy efficiency. The approach of this study not only can reduce the amount of greenhouse gas emissions but also to achieve a win-win strategy for the economy, energy, and environmental protection.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

FIGURE 9 Investment payback years. Note: Energy conservation of natural gas per year 254 273 M³, assume the unit price of natural gas is US$ 0.31/M³.
FIGURE 10  A, The effect of air volume on heat extraction with outlet temperature at 180°C. B, The effect of air volume on heat extraction with outlet temperature at 170°C. C, The effect of air volume on heat extraction with outlet temperature at 160°C. D, The effect of air volume on heat extraction with outlet temperature at 150°C.
FIGURE 11  The relationship between outlet temperature and enthalpy curve. Flue gases composition H2O (4.4%), CO2 (0.6%), O2 (20%), N2 (75%). Flow rate: 770 Nm³/min (20°C, 1 atm). Standard atmosphere (20°C, 1 atm): The density of this mixed flue gases is 1.1841 kg/m³

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