



Integration between energy and exergy analyses to assess the performance of furnace regenerative and ammonia decomposition systems

Mostafa El-Shafie^{a,*}, Shinji Kambara^a, Yukio Hayakawa^a, A.A. Hussien^b

^a Gifu University, Environmental and Renewable Energy Systems Division, Graduate School of Engineering, 1-1 Yanagido, Gifu, 501-1193, Japan

^b Mechanical Power Engineering Department, Faculty of Engineering, Minoufiya University, Shebin El-Kom, Egypt

ARTICLE INFO

Article history:

Received 12 January 2021

Received in revised form

24 April 2021

Accepted 27 April 2021

Available online 8 May 2021

Keywords:

Exergy

Entropy generation

Hydrogen production

Energy efficiency

ABSTRACT

Energy and exergy analyses were performed on a glass furnace regenerator and hydrogen production via thermal catalytic ammonia decomposition. A novel integration between energy and exergy analyses was suggested to predict the performance of thermodynamic and hydrogen production systems. It was found that the heat recovered by the combustion air of the south side regenerator was higher than that on the north side because of the fouling effect of the deposit materials and the heat lost through the regenerator walls. The maximum energy and exergy efficiencies of the south side regenerator were 98% and 93%, respectively, while those of the north regenerator side were 96.3% and 80%, respectively. The integration between energy and exergy analyses was also applied to investigate the performance of H₂ production from the catalytic NH₃ decomposition system. The conversion rate results proved that an increase in the ammonia feeding pressure was unfavorable. Moreover, the maximum energy and exergy efficiencies of the NH₃ thermal decomposition system were 73.5% and 13.34% at a feeding pressure of 100 kPa, respectively. Furthermore, the non-equilibrium of the system is identified from the integrated effectiveness and entropy generation number.

© 2021 Elsevier Ltd. All rights reserved.

1. Introduction

Exergy, or second law efficiency, has played an increasingly important role in design optimization and problem modeling and formulation in most recent engineering thermodynamics studies. Thermodynamics, entropy generation, and exergy analysis methods are mostly applied in modern engineering systems [1–3]. These engineering tools lead to the best use of energy resources, such as energy transformation and power production devices. In addition, energy is a thermodynamic analysis tool and a property of state; the total energy amount does not change during interactions [4]. The second law of thermodynamics showed the quality of the energy used by the system, as well as the quantity. Analysis of the second law of thermodynamics is based on exergy and entropy concepts. Hence, the second law elaborates on the quality of energy and its relationship with the surroundings. The quality term is referred to as “exergy”; however, equivalent names were found

from our literature review, such as available energy, availability, work capability, etc. Exergy can be defined as the maximum available work that can be produced by the system as it comes into equilibrium with its surroundings. Exergy analysis was obtained as a function of the entropy relationships. Entropy is expressed in terms of system irreversibility, which allows the progress of the non-equilibrium process to be investigated [5]. The exergy is destroyed and cannot be converted due to system irreversibility. Exergy analysis was established through the interfaces between thermodynamics, heat transfer, and fluid mechanics. Various studies have investigated the relationship between global warming and greenhouse gases (GHGs). Most GHGs are emitted from fossil fuel combustion and industrial applications [6–8]. Therefore, this study will focus on discussing and evaluating the performance of two thermodynamic systems (a glass furnace regenerator and hydrogen production from catalytic ammonia decomposition). The glass industry is a highly energy-intensive thermodynamic process. Based on the melting process operating temperature of 1400–1500 °C, the fuel consumption is too high [9]. In addition, the waste heat from the outlet flue gases is too high; therefore, regenerative systems are utilized to recover part of the waste heat for

* Corresponding author.

E-mail address: mostafaelshafie81@gmail.com (M. El-Shafie).

Nomenclature		$\dot{E}X$	Exergy (kW)
E	Energy (m^2)	<i>Greeks</i>	
\dot{E}	Rate of net energy (kWs^{-1})	η	Efficiency (%)
h	Specific enthalpy ($kJ\ kg^{-1}$)	<i>Subscripts</i>	
\dot{m}	Mass flow ($kg\ s^{-1}$)	0	environment, initial state
R	Specific gas constant ($J\ kg^{-1}K^{-1}$)	ch	chemical
P	Pressure (atm)	dest	destroyed
Q	Heat (kW)	ex	exergy
\dot{Q}	Heat rate ($kW\ s^{-1}$)	en	energy
r	Reaction rate	in	inlet
s	Entropy ($kJ\ kg^{-1}\ K^{-1}$)	kin	kinetics
T	Temperature (K)	out	outlet
T_0	Temperature of the environment, 300 K	P	Location p
\dot{W}	Work rate ($kJ\ s^{-1}$)	Pot	potential
EX	Specific exergy ($kJ\ kg^{-1}$)		

preheating the combustion air. The performance of an industrial glass furnace regenerator has been investigated [10]. The blockage prediction of the furnace regenerator was analyzed based on the design and operating parameters [11]. A thermal performance model was developed to predict the fouling caused by the condensate materials inside the regenerator checkers [12,13]. Most regenerator performance studies have been developed using the first and second laws of thermodynamics [14]. Owing to the important assessment of the second law or exergy efficiency analysis, it has been widely applied for different heat exchanger types [15–22]. Moreover, limited exergy analysis studies have been conducted on glass furnace regenerators.

In addition to using the available energy efficiently, it is important to eliminate the environmental impact of current industrial applications. The environmental impact of fossil fuels has become an urgent global issue. Hydrogen is a clean energy carrier and could be a future solution to all environmental issues. Therefore, hydrogen fuel is considered the best solution for environmental issues concerning conventional fuels. Many efforts have been made to develop new alternative methods for hydrogen carriers and storage [23,24]. Hydrogen production from ammonia decomposition has more advantages than other hydrogen carriers; for example, ammonia gas is a Cox-free H_2 carrier and has a higher gravimetric density than methanol, i.e., 17.7 wt% compared to 12.8 wt% [25,26]. Hydrogen can be produced from ammonia via plasma and thermal decomposition processes [26,27]. The life-cycle assessment of renewable ammonia and its environmental impact have been investigated [28]. Energy and exergy analyses have been investigated for different hydrogen production methods, e.g., ammonia decomposition systems using dielectric barrier discharge plasma [29]. Catalytic materials, including Ru, Ni, and Fe, are used to enhance the ammonia decomposition process [30]. Ruthenium catalytic materials have a high activation impact on the decomposition of ammonia gas [31,32]. Different reactor configurations and types have been utilized for the decomposition of ammonia [33]. The most common reactor type used in ammonia decomposition is the packed bed reactor but the scaling-up process has some deficiencies and cannot meet the distributed power system requirements [34]. Therefore, more efforts are required to provide more efficient reactors with a good residence time and heat transfer [35,36]. Furthermore, more advanced analysis of the current system, such as exergy or second law analysis, can improve system performance and further design concepts [37–39]. Exergy analysis has been utilized to optimize the ammonia gas production

processes [40,41]. In addition, the exergy analysis information of thermal ammonia decomposition is typically important for developing future process designs [42].

In this study, the energy and exergy analyses of the glass furnace regenerator and hydrogen production from thermal catalytic ammonia decomposition systems are introduced. Detailed fundamental analyses of the 1st and 2nd laws of thermodynamics were investigated. A new combination factor (integrated effectiveness factor) between the 1st and 2nd laws is suggested to evaluate the thermodynamic systems. Moreover, the integrated effectiveness factor (*IEF*) is compared with other evaluation factors, such as the quality factor and entropy generation number (N_s) for thermodynamic and hydrogen production systems. The heat recovery from the glass furnace regenerative system was analyzed via energy, exergy, and *IEF* to predict system deterioration. The exergy or second law efficiency analysis is provided for hydrogen production from thermal ammonia decomposition in a catalytic cylindrical-type reactor. Ruthenium catalytic material ($Ru-Al_2O_3$) was used to improve the dissociation of ammonia gas. The energy and exergy analyses were conducted at different reactor temperatures. The effect of the feeding pressure on the decomposition process was evaluated. Moreover, entropy generation and exergy destruction are determined and the energy and exergy results are compared. In addition, the *IEF* was compared with the quality factor and entropy generation number (N_s).

2. Exergy analysis

Thermodynamic analyses permits the well-known performance and efficiency behavior of the conversion of energy from one form to another. Exergy analysis can be regarded as an advanced tool for analyzing energy conversion processes. The thermodynamic inefficiencies and irreversibility of the system design can be determined using the exergy tool. Moreover, the exergy concept was established to express the quality of energy utilized by the system. In addition, it demonstrates the disordered energy forms that are characterized by entropy. Conversely, the other ordered energy forms that are not involved in entropy are completely converted via work interactions and other energy forms.

To determine the quality variable of various disordered energies in thermal and chemical plants, the universal quality standard, *exergy*, is used. Exergy can be defined as the maximum work that can be obtained from the available input energy using the environmental state conditions as the reference parameters. The energy

quality concept or exergy analysis is mainly used in the exergy balance of thermal systems. It seems that the exergy balance is similar to the energy balance but there is a fundamental difference in that the energy balance is conducted using the law of conservation of energy or the 1st law of thermodynamics while the exergy balance is a statement of the law of degradation of energy or the 2nd law of thermodynamics. The degradation of energy is expressed in all real processes and process irreversibility. The irreversibility of the system is determined via entropy generation. The energy balance analysis concept of the control region can generally be considered for three types of work transfer, heat transfer, and energy transfer associated with mass transfer. Furthermore, exergy analysis can help the user to obtain the best decision for system improvement [43,44].

The mass balance equation of a steady-state system can be expressed as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

where \dot{m} is the mass flow rate and the subscripts *in* and *out* refer to inlet and outlet, respectively. The energy balance between the total energy input and total energy output is defined as follows:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (2)$$

where the total rate of energy input is \dot{E}_{in} and \dot{E}_{out} is the total energy output. Most studies neglect potential and kinetic energy changes [45],

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \quad (3)$$

where the rate of net heat input is \dot{Q} , \dot{W} is the net work output, and h is the specific enthalpy. The energy efficiency is defined as the ratio between the total energy output and total energy input, as follows:

$$\eta_{en} = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad (4)$$

The exergy balance should be appropriately analyzed, corresponding to the energy transfer forms. Exergy analysis is a helpful process for evaluating the quality of utilized energy and describes how the system is far from a reversible process. The exergy is equal to the maximum available work from a given energy. The specific exergy can be determined from the exergy components as follows [46]:

$$Ex = Ex_{ke} + Ex_{pot} + Ex_{ph} + Ex_{ch} \quad (5)$$

The kinetic and potential energies are determined when the total energy stream is fully converted into work. Therefore, the kinetic and potential energies can be determined based on an environmental reference:

$$Ex_{ke} = \dot{m} \frac{C_0^2}{2} \quad (6)$$

and,

$$Ex_{pot} = \dot{m} g Z_0 \quad (7)$$

where C_0 is the bulk velocity of the fluid stream, g is the gravitational acceleration, and Z_0 is the altitude above sea level. The physical exergy is equal to the maximum amount of work obtained when the substance stream is brought from the initial state to the

environmental state. The physical exergy (Ex_{ph}) can be derived using the following equation:

$$Ex_{ph} = (h - h_0) - T_0(s - s_0) \quad (8)$$

The chemical exergy of a substance is defined as the maximum available work obtained when the substance is brought from the environmental state to the dead state, involving heat transfer and substance exchange with the environment. The chemical exergy is also equal to the minimum work required for the synthesis. The chemical exergy of the gaseous mixture is determined from the following relation [47]:

$$Ex_{ch} = RT_0 \ln \frac{P_0}{P_p} \quad (9)$$

where R is the universal gas constant. The difference between the total exergy input and exergy output is exergy destruction.

$$\sum \dot{Ex}_{dest} = \sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} \quad (10)$$

The exergy efficiency is formulated in different ways and can be defined as the ratio of the total exergy output or useful exergy to the total exergy inputs as the utilized exergy [48]:

$$\eta_{II} = \eta_{ex} = \frac{\sum \dot{Ex}_{out}}{\sum \dot{Ex}_{in}} = 1 - \frac{\sum \dot{Ex}_{dest}}{\sum \dot{Ex}_{in}} \quad (11)$$

The exergetic efficiency increases to a maximum when the exergy destruction or system irreversibility is minimized. The exergy of the thermodynamic system (thermal exergy) can be determined based on the quality factor or can be referred to in other studies as the dimensionless exergetic temperature. In a special case, i.e., when the surface temperature (T_s) is equal to the environmental temperature (T_0), it is equal to the Carnot efficiency.

$$Quality\ factor = 1 - \frac{T_0}{T_s} \quad (12)$$

The entropy concept depends on the equilibrium state and the reversible process in classical thermodynamics [49]. The entropy generation term measures the irreversibility or non-equilibrium processes. All irreversible processes are accompanied by an increase in entropy; hence, entropy generation is identified as the inequalities and irreversibility of the system. Entropy generation can be determined from the following relation [10]:

$$S_g = \int_{t_1}^{t_2} \dot{S}_g dt \quad (13)$$

The entropy generation number (N_s) can be defined as the ratio between the exergy destroyed to the total exergy input. This relationship determines the irreversibility degree (I_d), i.e., a higher irreversibility degree (I_d) indicates a greater destruction of exergy.

$$N_s = I_d = \frac{Ex_{dest}}{Ex_{in}} \quad (14)$$

Hence, the exergy efficiency can be rewritten as follows:

$$\eta_{II} = 1 - I_d \quad (15)$$

The previous equation demonstrates that the second law efficiency improves and the system performance will be enhanced by minimizing the entropy generation number. From the previous discussion, it is clear that the second law of thermodynamics revolves around the concepts of exergy and entropy.

2.1. Integrated effectiveness factor [IEF]

For a deeper analysis of the thermodynamic systems, the *IEF* is suggested for combining the energy and exergy terms in the thermodynamic laws. The integration analysis concept will declare how efficiently the system is performing. Firstly, the energy concept or the first law of thermodynamics cannot tell us how the system performs work and it does not give information about the inability of energy transform from one form to another. The energy is conserved and cannot be destroyed; additionally it is a measure quantity only. In contrast, the exergy analysis or the second law efficiency was investigated to measure the system irreversibility and for more useful analysis to improve the efficiency. The exergy term is considered a part of the energy that can be regarded as a useful value to reveal the system design and efficiency. The total difference between the total sum of exergy input and total exergy output is the exergy destroyed by system irreversibilities. Moreover, it was seen that the integration between energy and exergy analysis would enable us to determine the loss location, types, and magnitudes to use the available energy sources more efficiently. The *IEF* can be defined as the effect of the exergy destroyed on the total energy input and output exergy. In addition, *IEF* can be defined as the ratio of the system irreversibility loss (exergy destruction) to the maximum system loss. The *IEF* term is an indicator of how the system uses the available energy effectively and shows how the system is far from reversible. The integration effectiveness factor is expressed as follows:

$$IEF = \frac{Ex_{dest} [W]}{E_{in} [W] - Ex_{out} [W]} [-] \quad (16)$$

This factor can be used to evaluate the ability of a system to effectively use the available energy. Furthermore, the *IEF* can be defined by combining the energy and exergy balance analysis. This combination will provide an irreversibility effect on both the total energy input and the maximum useful output exergy. Fig. 1 shows the exergy and energy input and output through the system. The *IEF* can also be seen as a ratio of the actual energy or exergy destruction amount to the maximum possible energy difference through the system. It can be considered that the *IEF* is a quantitative method for evaluating the imperfection of thermodynamic systems. The integration between energy and exergy analysis using the *IEF* that includes the total energy input, the maximum useful exergy, and the exergy destroyed enables to determine the inefficiencies of the energy systems. Moreover, this factor improves when the exergy destroyed or the irreversibility term is reduced.

Through case studies, the *IEF* is compared with the entropy generation number (*Ns*), quality factor, as well as the effectiveness of the glass furnace regenerator. Furthermore, the integration

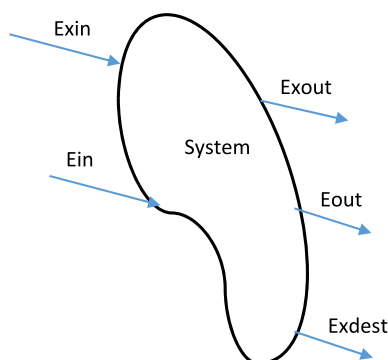


Fig. 1. Energy and exergy flow through the system.

between energy and exergy analysis is also performed for the hydrogen production from catalytic ammonia decomposition.

3. Analysis of the glass furnace regenerator

Energy and exergy analyses of the glass furnace regenerator were performed. The integration and combination of both the 1st and 2nd laws of thermodynamics were applied to the regenerative system. Glass melting reactions occur at a high temperature range of 1400–1500 °C in a confined refractory furnace. A typical glass furnace regenerator experimental analysis was conducted on an actual operating glass factory located at the El-Araby Group Company, Quesna Industrial City, Egypt. The performance of the same glass furnace regenerator was previously investigated by El-Behery et al. 2016 [10]. A natural gas fuel type was used as the input fuel. An actual printout photo of the glass furnace regenerative control system is shown in Fig. 2. The regenerator-type heat exchanger is composed of two refractory chambers, north and south. This photo shows that the combustion air is preheated from the stored heat on the north side while the flue gases pass through the south side chamber. Two burners are installed after the regenerator in the north and south chambers; therefore, to preheat the combustion air, the flue gases and combustion air paths are interchanged every 15 min.

The main objective of using the regenerative system is to recover heat and preheat the combustion air before entering the combustion or melting chamber. The heat transfer inside the regenerator chambers depends on the regenerator area and the ability of the regenerator bricks to absorb and lose heat. Therefore, brick layers should have good thermal stability, high refractoriness, and heat storage [10]. The regenerator chamber layers are composed of two brick layer types: alumina-silica and silica bricks. The regenerator chambers were arranged as a group of flow channel passages on each side. In addition to the regenerator material and their arrangements, the ability of the regenerator to absorb heat was mostly dependent on the flow behavior through the regenerator bricks channels [10]. The ingress air enters from the outside to the flue gas side because of the negative pressure produced by the draught system. Moreover, some of the combustion air stream escapes from the regenerator air stream side to the environment.

The regenerator system mass balance can be calculated as:

$$\dot{m}_{f,i} + \dot{m}_{l,i} = \dot{m}_{f,o} \quad (17)$$

$$\dot{m}_{a,i} - \dot{m}_{l,o} = \dot{m}_{a,o} \quad (18)$$

The combustion air stream absorbed the heat stored in the regenerator brick layers during the flue gas stream. Furthermore, heat was lost from the regenerator outside the walls during the heating and cooling periods. The regenerator energy balance is determined from the available flue gas heat, the heat losses from the regenerator wall, the heat absorbed by air, the exchanged heat by ingress air, and the heat loss in the combustion air leakage.

$$\dot{m}_{f,i} h_{f,i} + \dot{m}_{a,i} h_{a,i} + \dot{m}_{l,i} h_{l,i} = \dot{m}_{f,o} h_{f,o} + \dot{m}_{a,o} h_{a,o} + \dot{m}_{l,o} h_{l,o} + \dot{Q}_w \quad (19)$$

where *h* is the enthalpy of gas mixture. The regenerator efficiency can be determined using Equation (4). In addition, the regenerator performance can be determined from the effectiveness parameter, which can be defined as the actual heat exchange to the maximum heat that can be exchanged during regenerator cooling and heating periods [50]:

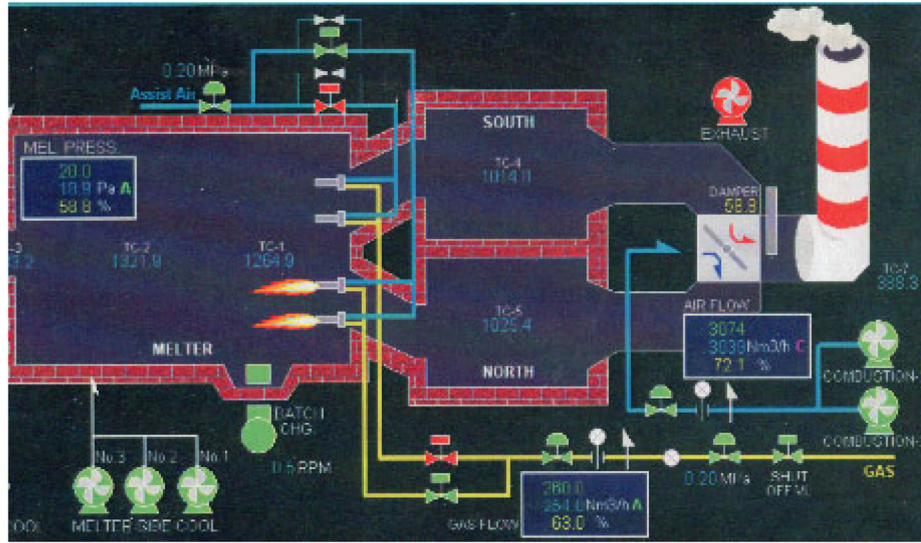


Fig. 2. Image of actual printout of regenerative system.

$$\epsilon_{\text{heating}} = \frac{Q_f}{Q_{\text{max}}} = \frac{\dot{m}_f C_{pf} (T_{f,i} - T_{f,o})}{(\dot{m}C_p)_{\text{min}} (T_{f,i} - T_{a,i})} \quad (20)$$

$$\epsilon_{\text{cooling}} = \frac{Q_a}{Q_{\text{max}}} = \frac{\dot{m}_a C_{pa} (T_{a,o} - T_{a,i})}{(\dot{m}C_p)_{\text{min}} (T_{f,i} - T_{a,i})} \quad (21)$$

The minimum heat capacity $(\dot{m}C_p)_{\text{min}}$ is equal to the air heat capacity because the flue gas flow rates are always higher than air.

The exergy analysis of the regenerative system can be determined from heat exchange and mass flow. Exergy analysis is a helpful tool for optimizing thermodynamic systems and industrial applications [51]. The exergy change in the flue gas stream can be calculated as follows:

$$\Delta \dot{E}x_f = \dot{m}_f (Ex_{f,i} - Ex_{f,o}) = \dot{m}_f [(h_{f,i} - h_{f,o}) - T_0 \Delta s_g] \quad (22)$$

Similarly, the combustion air exergy can be obtained as follows:

$$\Delta \dot{E}x_a = \dot{m}_a (Ex_{a,o} - Ex_{a,i}) = \dot{m}_a [(h_{a,o} - h_{a,i}) - T_0 \Delta s_a] \quad (23)$$

The total exergy of the hot gas stream is not completely recovered by the combustion air because of entropy generation during the heat exchange process. Therefore, the destroyed exergy can be written as:

$$\Delta \dot{E}x_{\text{dest}} = (\Delta \dot{E}x_f - \Delta \dot{E}x_a) = T_0 \dot{S}_{\text{gen}} \quad (24)$$

where

$$\dot{S}_{\text{gen}} = \dot{m}_f \Delta s_g + \dot{m}_a \Delta s_a \quad (25)$$

The exergetic efficiency or the second law efficiency can be expressed as follows:

$$\eta_{\text{II}} = \eta_{\text{ex}} = \Delta \frac{\dot{E}x_a}{\Delta \dot{E}x_f} = 1 - \Delta \frac{\dot{E}x_{\text{dest}}}{\Delta \dot{E}x_f} \quad (26)$$

3.1. Regenerator case results

The main function of a regenerator is to preheat the combustion air to save energy and natural gas fuel costs. The performance of heat exchange through the furnace regenerator is discussed in this paper. The quality factor, entropy generation number, irreversibility degree, and *IEF* were compared. Fig. 3 compares the performance of the glass furnace regenerator while combustion air passes through the south side, in terms of energy and exergy efficiencies with respect to ignition time. It was found that the energy efficiency is higher than the exergy efficiency owing to the system's irreversibility. In addition, the energy and exergy efficiencies increased to 98% and 93%, respectively, as the ignition time reached a maximum value. The energy and exergy analyses of the north side during the cooling period are shown in Fig. 4. The exergy results are lower than

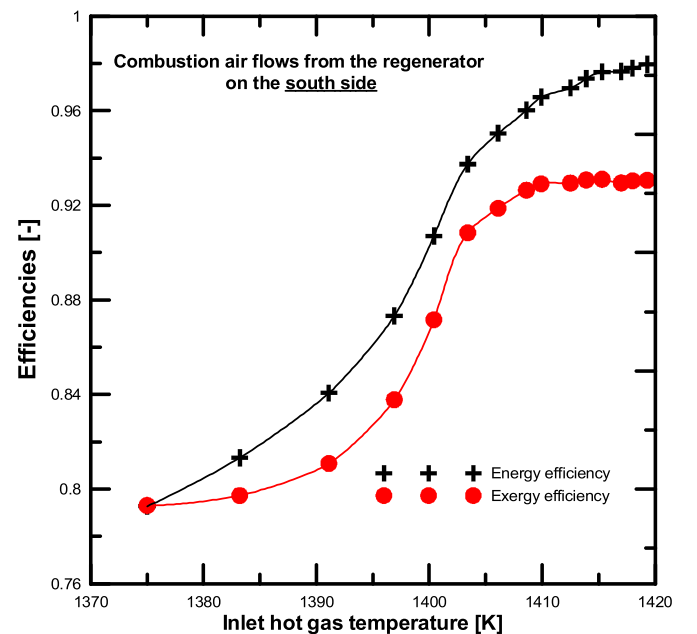


Fig. 3. Energy and exergy analysis of the regenerator south side.

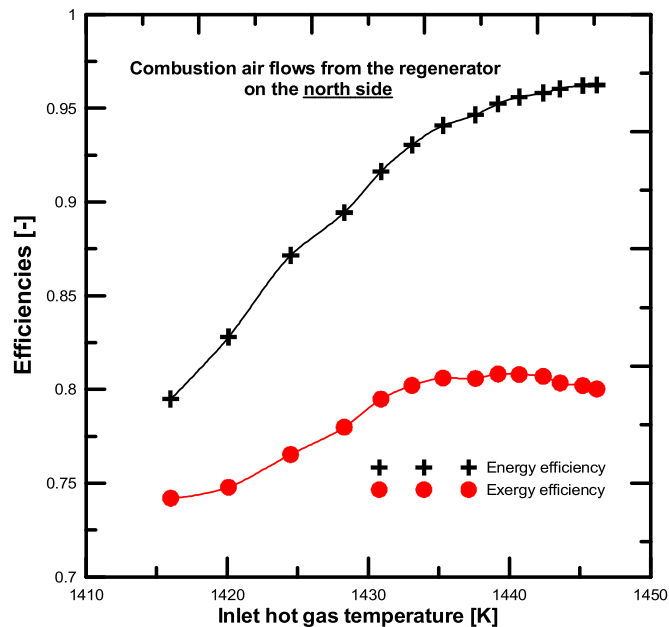


Fig. 4. Energy and exergy analysis of the regenerator north side.



Fig. 5. Actual upper side regenerator channels photo.

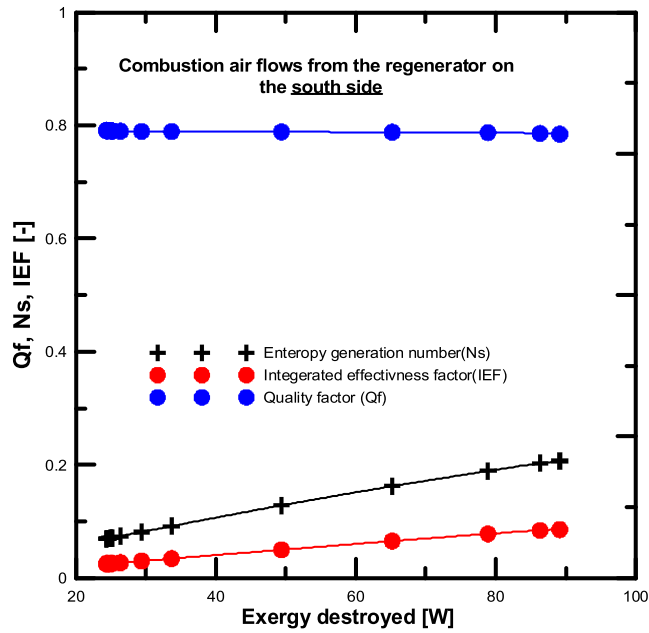
those obtained from the south side during the cooling period. The performance behavior of the regenerator on both sides is not similar because the north side is closer to the batch charger (raw materials) compared to the south side, which leads to high fly ash deposition on the north side. This fly ash creates a fouling layer inside the regenerator checkers causing partial blockage. The deposit layer was accumulated on the regenerator checker brick with the glass furnace operating time. The fouling layer effect was appeared in the decreasing of the overall heat transfer coefficient and heat transfer area which causes an increase of the outlet exhaust gas temperature. The cleaning process was carried out to remove the fly ash deposit layer on the regenerator checkers during the furnace overhaul. It has been reported that the regenerator performance was enhanced after the cleaning process [10]. In addition, it was found that the regenerator's north side exergy results were lower than those obtained from the south side influenced by the heat transfer losses. Thus, the outlet air temperature from the south side was higher than that on the north side. These regenerator analysis results are confirmed with our previous study that the fouling and deposit layer affect the overall heat transfer coefficient and heat transfer area inside the regenerator channels [10]. The maximum obtained energy and exergy efficiency of the regenerator on the north side were 96.3% and 80%, respectively.

The regenerator air and flue gas streams are separated, the regenerator wall bricks are heated by the flue gases, and the combustion air absorbs heat from the high-temperature regenerator checkers and channels. The blockage of the regenerator channels is an important factor that leads to heat transfer losses. An actual regenerator channel photo is shown in Fig. 5. The fly ash or deposit material layer reduces the heat transfer area and reduces the heat absorbed by the regenerator wall; consequently, the outlet combustion air temperature decreases.

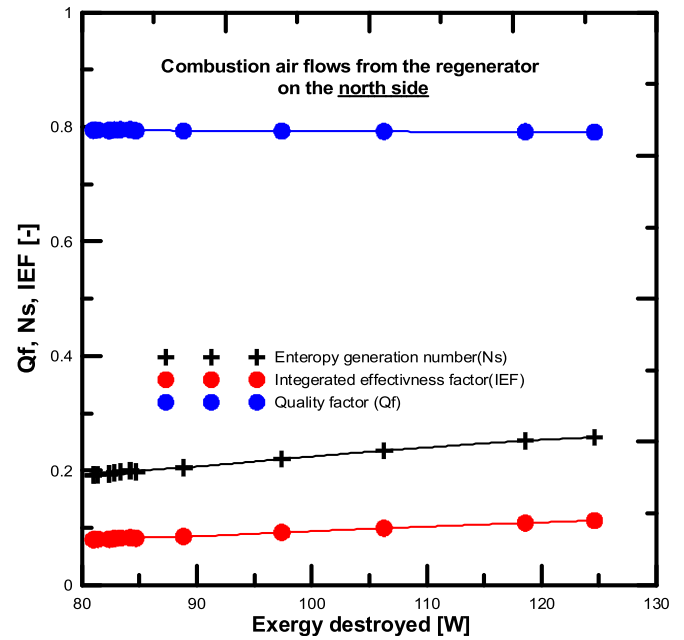
The quality factor (Q_f), N_s , and IEF results versus the destroyed exergy of the south side of the regenerator are shown in Figure (6a). It was observed that the quality factor results were too high compared to the IEF and N_s . The quality factor is sometimes referred to as the dimensionless exergetic temperature and is equal to the Carnot efficiency in the special case when the surface temperature (T_s) is equal to the environmental temperature (T_0). The losses due

to the irreversibility effect were clearly defined by the entropy generation number (N_s) and the IEF . In addition, it was found that N_s and IEF increased with the destruction of exergy. Figure (6b) shows the energy and exergy efficiency behavior compared with the N_s and IEF trends. The energy and exergy efficiency decreased with an increase in N_s and IEF , indicating that the exergy destruction or entropy generation increased. The combination of energy and exergy balance factor (IEF) can effectively express the capability of the system to use the available energy. Therefore, the heat stored in the south side of the regenerator walls is not completely transferred to the combustion air because of system irreversibility. Fig. (7a) illustrates the behavior of the evaluation factors versus the destroyed exergy of the north side of the regenerator. It is clear that the N_s and IEF of the regenerator north side are similarly increased as the exergy is destroyed. The changes in the energy and exergy efficiency results of the north side chamber with the N_s and IEF factors are shown in Figure (7b). It was noted that the increase in N_s and IEF resulted in a decrease in energy and exergy efficiency because of the irreversibility effect. The losses in the north side chamber are higher than those in the south side because the fouling and deposit material layer thickness is greater than that on the south side. The blockage of the regenerator checkers reduces the heat transfer area and leads to a reduction in the regenerator performance. The north side regenerator chamber is much closer to the batch charger (raw material); consequently, a large amount of fly ash is sublimated during the north side chamber heating period. Therefore, the regenerator chambers, especially the north side, should be cleaned periodically to reduce heat transfer losses. It has been proven that regenerator cleaning enhances performance and effectiveness [52]. A comparison of the IEF behavior between the south and north side chambers is depicted in Fig. 8. It is clear that the heat recovery losses on the north side are higher than those on the south side because of the regenerator channel blockage and the destroyed exergy is too high. It can also be noticed that the heat transfer rate of the regenerator depends upon the heat transfer cross-sectional area, overall heat transfer coefficient, and the temperature difference between both the combustion air and flue gas streams.

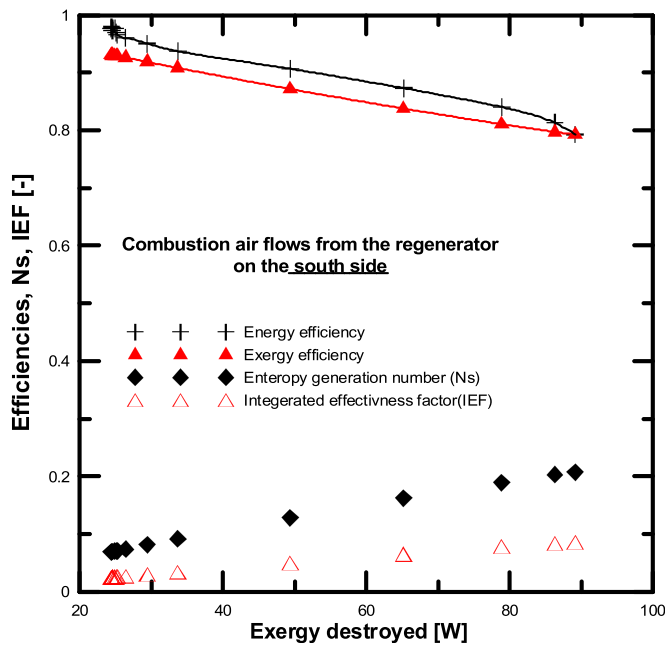
The IEF can predict the regenerator performance and heat recovery losses (wall losses, air leakage, and blockage losses). The increase in the IEF indicates that the irreversibility or heat transfer losses due to the regenerator blockage are too high. Furthermore, the combination factor or IEF accurately shows how irreversibility influences thermodynamic systems, combining the total input energy and the exergy output or useful exergy. The IEF can be used to express thermodynamic systems far from the reversible process. The regenerator cooling and heating effectiveness can be calculated



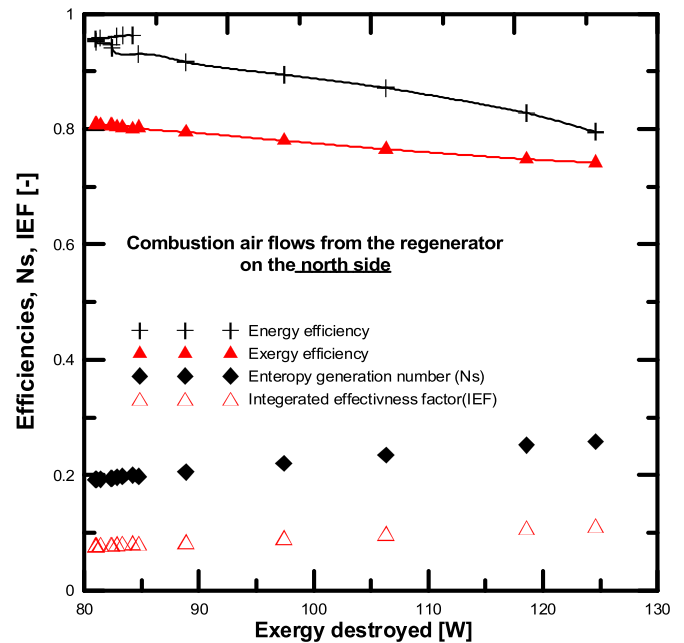
(a)



(a)



(b)



(b)

Fig. 6. The quality factor, Ns, and IEF versus exergy destroyed of the south side.

Fig. 7. The quality factor, Ns, and IEF versus exergy destroyed of the north side.

according to equations (20) and (21). Fig. 9 presents the variation in the effectiveness on both sides compared with the *IEF*. The regenerator effectiveness of the south side regenerator was higher than that obtained from the north side. In contrast, the *IEF* of the north side is higher than that of the south side due to the regenerator heat loss through the walls and the deposit material fouling layer inside the regenerator channels. As a result, the entropy generation of the regenerator on both sides decreased with operation time, which led to a decrease in the exergy destruction and enhanced exergy efficiency. The performance of the glass furnace regenerator was analyzed based on actual temperature measurements of

combustion air and flue gases at the regenerator inlets and outlets. The results showed that the regenerator performance was influenced by fly ash or deposit material fouling on the regenerator channel walls. Furthermore, the effect of the fouling layer clearly appeared in the regenerator *IEF* and performance results. Therefore, the regenerator on both sides should be cleaned periodically based on the measurements and performance results; it has been reported that regenerator cleaning increased heat recovery from the combustion air for both sides of the regenerator. In addition, the outlet high-temperature flue gases from industrial applications can be typically utilized as a heat source in hydrogen production

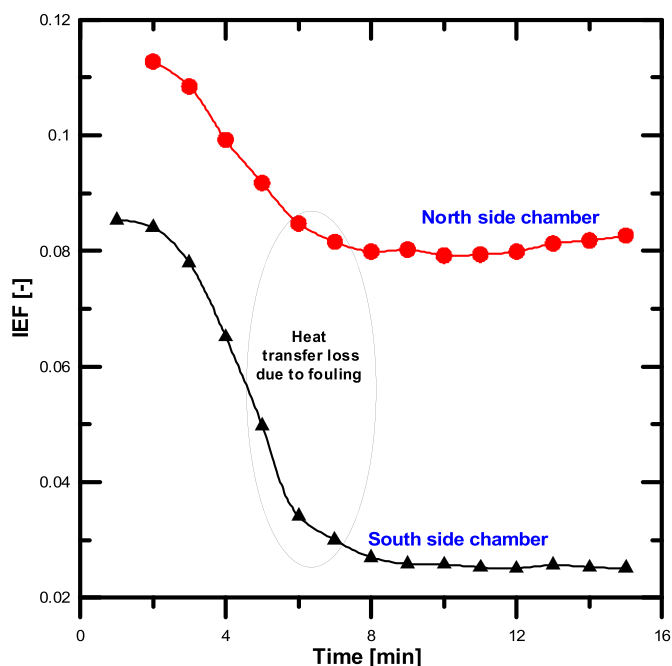


Fig. 8. The change of the IEF of both regenerator chambers.

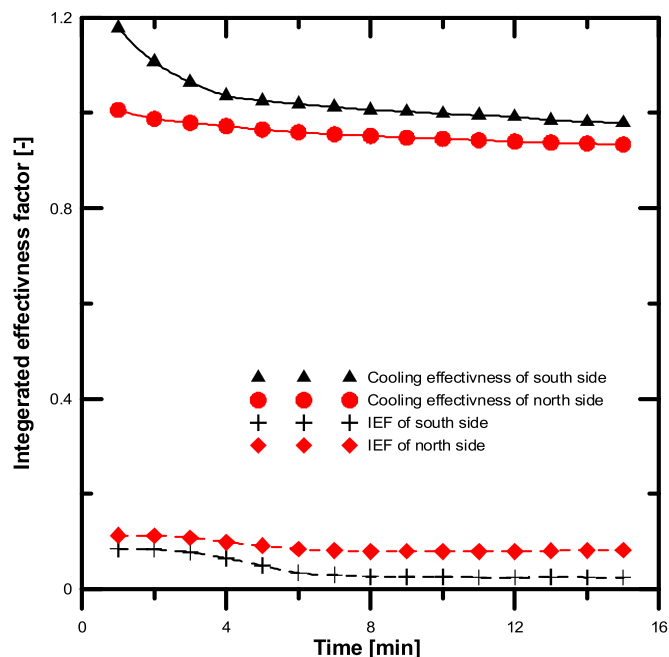
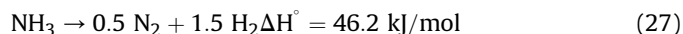


Fig. 9. Comparison between regenerator chambers effectiveness and IEF.

systems that will eliminate the environmental impact. Some typical waste heats could be considered to produce water vapor for H_2 production from non-thermal plasma or to raise the reactor temperature in some applications.

4. Hydrogen production from ammonia gas

Hydrogen production from ammonia decomposition is an energy-intensive process and the thermal decomposition reaction of ammonia gas into hydrogen and nitrogen gas can be written as follows:



H_2 production from ammonia gas was analyzed. A cylindrical-type reactor filled with ruthenium catalytic material was used for the thermal decomposition of ammonia gas. Fig. 10 shows the experimental setup for the ammonia decomposition system. The ammonia gas was fed into the reactor at a concentration of 100% and flow rate of 1.7 L/min. As protective measures ammonia decomposition experiment was carried out at proper ventilation area and stored separately. The ammonia feeding gas pressure was controlled in the range of 0–300 kPa. A Ru– Al_2O_3 catalyst with a diameter of 1 mm was mounted inside the reactor cylinder. Ruthenium has been reported to exhibit the highest activation results for the ammonia decomposition process [53,54]. The catalytic cylindrical reactor diameter and length were 1.6 cm and 30 cm, respectively. The reactor was heated in the temperature range of 473–773 K using a digital electric heating furnace. The feeding gas flow rate and pressure were controlled using a mass flow controller and pressure regulator. The decomposed hydrogen gas concentration was measured using a hydrogen gas analyzer. The glass wool material was revolved around the reactor to prevent heat loss.

4.1. Hydrogen production from ammonia gas results

Thermodynamic analysis alone is an unambiguous answer to the maximum output energy of the system. Therefore, the exergy analysis or the second law of thermodynamics can provide the best answer to the energy quality or the maximum available work from the system “exergy” [55]. The effect of the feeding pressure on NH_3 decomposition was investigated. Fig. 11 shows the maximum conversion rate at a heating temperature of 773 K. It has been reported that increasing the ammonia decomposition feeding gas pressure is unfavorable [25]. The results of this study confirmed that the maximum conversion rate was obtained at a low ammonia gas feeding pressure. The conversion rate of NH_3 gas reached 100% at a feeding pressure of 0 kPa (gauge pressure) and the conversion rate decreased with increased feeding pressure. The performance of the ammonia decomposition system can be defined by its energy efficiency. Fig. 12 shows the energy efficiency results at different heating temperatures and feeding pressures. The energy efficiency results of the feeding gas pressure of 0 kPa (gauge) were higher than those obtained at the other feeding gas pressures. In addition, it was found that the energy efficiency increased as the heating temperature increased. The maximum obtained energy efficiencies were 73.5%, 71.9%, 65.9%, and 64.8% at feeding gauge pressures of 0 kPa, 100 kPa, 200 kPa, and 300 kPa, respectively.

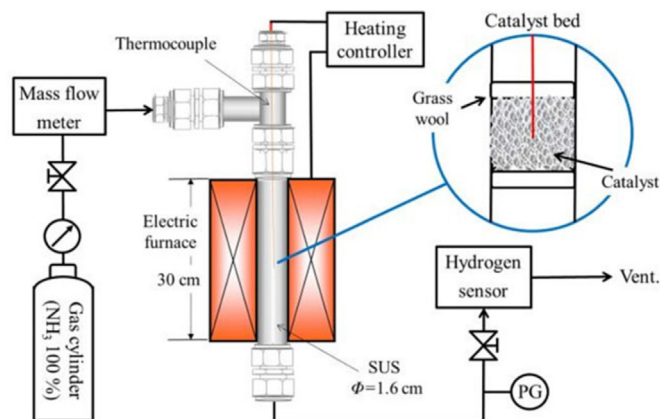


Fig. 10. Schematic diagram of catalytic thermal ammonia decomposition.

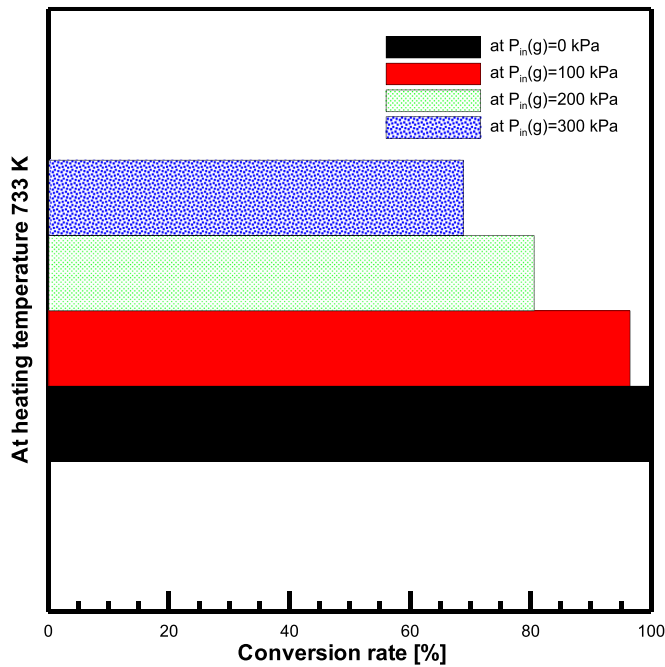


Fig. 11. The maximum conversion rate % from the catalytic NH₃ decomposition system at 773 K.

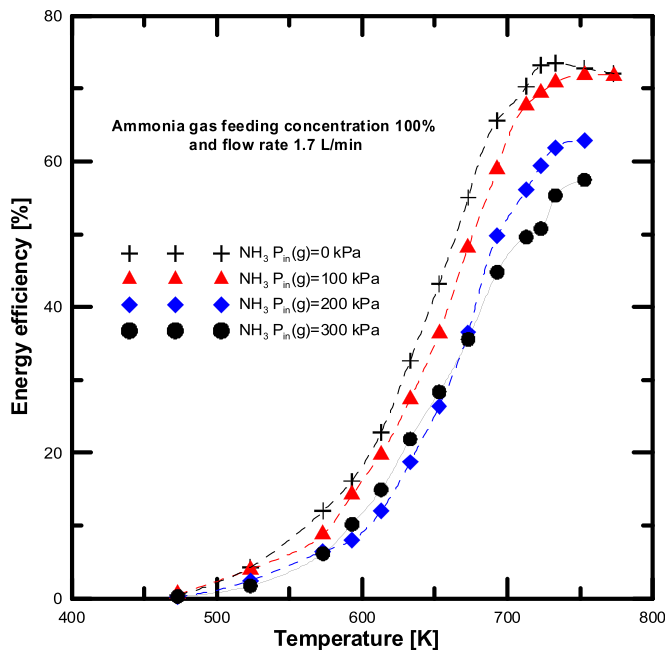


Fig. 12. Energy efficiency analysis at different heating temperatures.

The energy and exergy analyses of the ammonia decomposition system can modify the system design parameters to enhance system efficiency. Different parameters influence hydrogen production from ammonia decomposition, such as the feeding gas pressure reactor configuration and heat transfer. The irreversibility degree or non-equilibrium can be determined by classical thermodynamic analysis or the second law of thermodynamics. The exergy destroyed is defined as the difference between the total exergy input and the total exergy output.

Fig. 13 shows the exergy destruction at different reactor

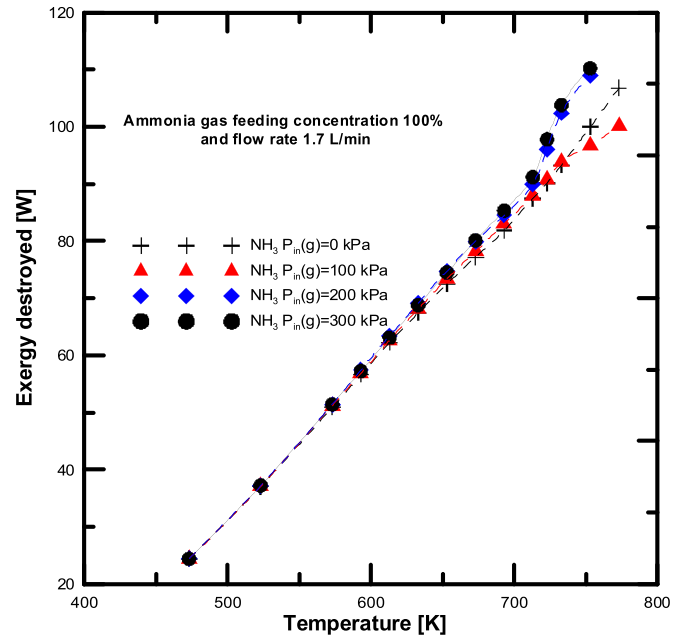


Fig. 13. Exergy destroyed analysis at different heating temperature.

temperatures and feeding pressures. The exergy destruction increased with the reactor heating temperature, as well as the ammonia feeding gas pressure. It was clear that hydrogen production from the ammonia decomposition system was subjected to the dissipative non-equilibrium process. The energy quality of the ammonia decomposition system can be expressed by applying the second law of thermodynamics. Fig. 14 presents the exergy efficiency at different reactor heating temperatures and pressures. The maximum exergy efficiency obtained was 13.34%, at a feeding gauge pressure of 0 kPa and a reactor temperature of 773 K. Furthermore, the entropy generation concept can express the non-equilibrium of the decomposition process. Moreover, the entropy

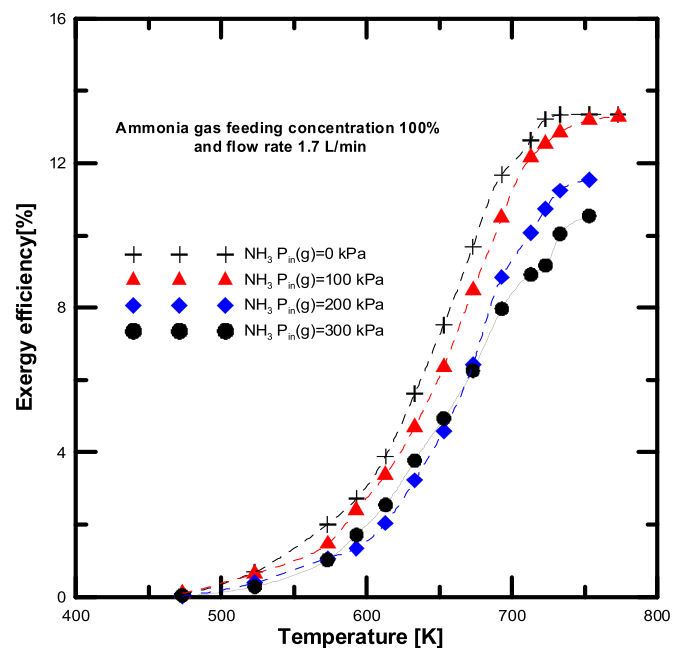


Fig. 14. Exergy efficiency results at different NH₃ feeding pressures and temperatures.

generation number (N_s) in modern thermodynamics indicates the degree of irreversibility.

Fig. 15 compares the changes in energy and exergy efficiency at different ammonia decomposition temperatures. It was observed that entropy generation or irreversibility reduced the second law or exergy efficiency. The maximum energy and exergy efficiencies of the thermal ammonia decomposition were 72% and 13.34%, respectively, at a reactor temperature of 773 K. The quality factor, entropy generation number (N_s), and IEF are shown in Fig. 16. The entropy generation quantity is related to the process of non-equilibrium or irreversibility.

In thermal NH_3 decomposition, it was found that the entropy generation number (N_s) decreased as exergy efficiency increased whereas the exergy destruction increased. In contrast, the IEF indicates the degree of irreversibility and the actual performance of H_2 production from thermal NH_3 decomposition. The IEF exhibited higher obtained values with the increase in destroyed exergy while the energy and exergy increased. The quality factor also increases with the destruction of exergy. An increase in the IEF indicates that the system losses and irreversibility are high. IEF can be used to optimize hydrogen production from ammonia decomposition systems. Recently, the concept of exergy has been used in different contexts to improve conversion systems [56]. Exergy analysis describes the energy quality and helps to estimate the most efficient condition of the decomposition system. Different parameters are influenced by the hydrogen production from the ammonia decomposition process, such as the reactor temperature, feeding pressure, reactor design and configuration, and heat and mass transfer. A comparison between the energy, second law efficiency, N_s , and IEF is shown in Fig. 17. It was observed that the second law efficiency result was lower than the energy efficiency, indicating that exergy was destroyed. It was clear how the H_2 production from the catalytic ammonia decomposition system was related to the entropy generation present in the IEF trend behavior. Hence, the analysis demonstrated that a more energy-efficient system is required. These results represent the deviation of the real ammonia decomposition system from its equilibrium state.

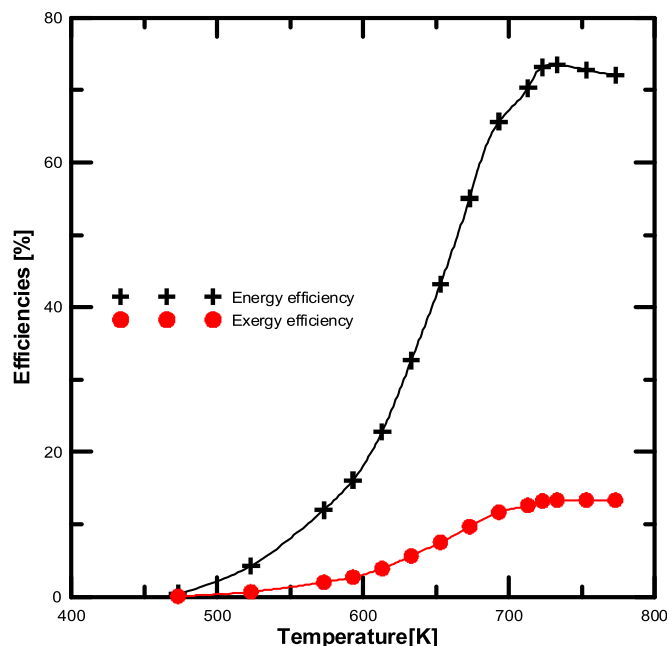


Fig. 15. Comparison between energy and exergy efficiency results.

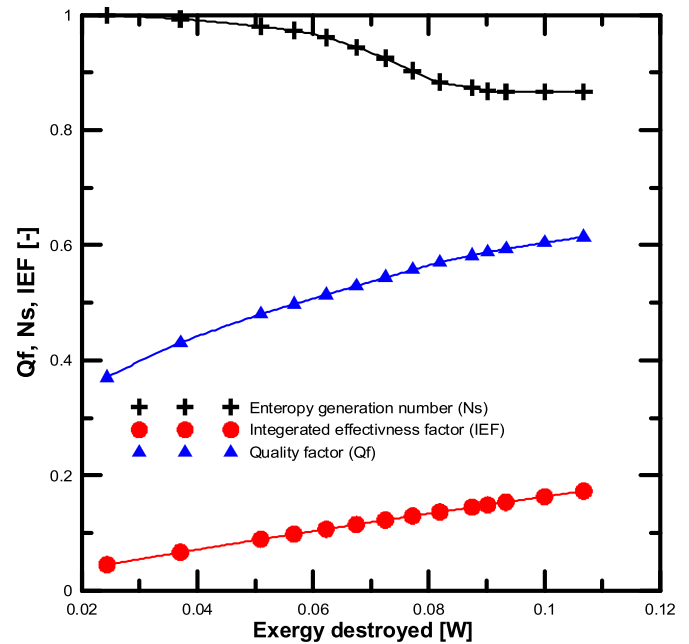


Fig. 16. Comparison between evaluation factor results.

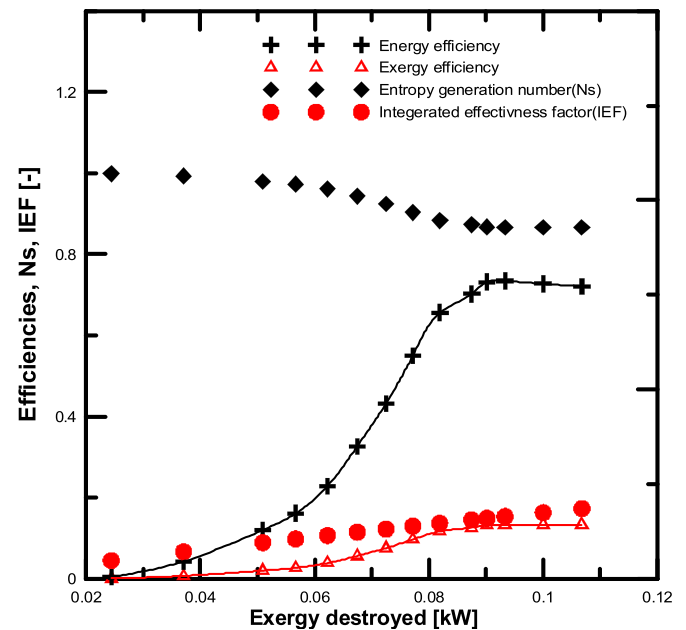


Fig. 17. Entropy generation number results at NH_3 feeding pressure 0 kPa (gauge pressure).

5. Conclusion

In the present study, the concepts of energy and exergy were used to analyze a glass furnace regenerator and hydrogen production from ammonia decomposition systems. Moreover, a novel IEF was suggested to evaluate the thermodynamic system performance and to provide the quantity of non-equilibrium processes. The quality factor and entropy generation number (N_s) were compared with the IEF . The IEF can express system non-equilibrium with its environment. The performance results of the glass furnace regenerator system are summarized as follows:

1. The heat recovered by combustion air during the cooling period of the south side of the regenerator is higher than that on the north side while the outlet flue gas temperature from the south side was low.
2. The energy and exergy efficiency of the regenerator south side is higher than that obtained from the north side of the regenerator because of the heat transfer losses from the regenerator walls and fly ash fouling layer inside the regenerator channels.
3. The *IEF* results on the north side of the regenerator are higher than those on the south side because the exergy destruction of the north side of the regenerator is high.
4. The cleaning process of the regenerator channels should be performed periodically to reduce heat transfer losses due to regenerator blockage.

The performance of hydrogen production from a thermal catalytic ammonia decomposition system was also investigated and the conclusions can be described as follows:

1. The conversion rate% results proved that the increase in ammonia feeding gas pressure is unfavorable [25] as the maximum result is obtained at a gauge pressure of 0 kPa.
2. The maximum energy efficiencies at feeding gauge pressures of 0 kPa, 100 kPa, 200 kPa, and 300 kPa were 73.5%, 71.9%, 65.9%, and 64.8%, respectively.
3. The maximum exergy efficiency was 13.34% at an ammonia gas feeding pressure of 0 kPa.
4. Moreover, the entropy generation number (N_s) was decreased by improving the exergy efficiency while the *IEF* increased because the exergy was destroyed and the total energy input was still high compared with the output exergy.

Finally, the exergy analysis and *IEF* can describe the inefficiencies of the thermodynamic systems and the energy and exergy efficiency can be enhanced by improving the system design parameters. A comparison between energy, exergy efficiency, and evaluation factors (quality factor Q_f , N_s , *IEF*) shows how the real systems deviate from their environment.

CRedit authorship contribution statement

Mostafa El-Shafie: Data curation, Writing – original draft, and, Software. **Shinji Kambara:** Conceptualization, Methodology, and, Supervision. **Yukio Hayakawa:** Visualization, Investigation. **A.A. Hussien:** Writing – review & editing, Reviewing, Editing, and, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank **Prof. Shinji Kambara** (Environmental and energy systems department–Gifu University–Japan) for his continuous support.

References

- [1] M.J. Moran, E. Sciubba, Exergetic analysis: principles and practice, *J. Eng. Gas Turbines Power* 116 (1994) 285–290.
- [2] S. Stecco, M.J. Moran (Eds.), *A Future for Energy*, Pergamon, Oxford, UK, 1990.
- [3] *Ecos '92*, in: A. Valero, G. Tsatsaronis (Eds.), *Proc. Int. Symp. Efficiency, Costs, Optimization and Simulation of Energy Systems*, Zaragoza, Spain, ASME Press, New York, 1992.
- [4] I. Dincer, Y.A. Cengel, Energy, entropy and exergy concepts and their roles in thermal engineering, *Entropy* 3 (2001) 116–149.
- [5] G. Gallavotti, Entropy, thermostats and chaotic hypothesis, *Chaos* 16 (2006) 384–389.
- [6] R.K. Pachauri, M.R. Allen, V.R. Barros, J. Broome, W. Cramer, R. Christ, J.-P. van Ypersele, Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 2014.
- [7] M. El-Shafie, S. Kambara, Y. Hayakawa, Hydrogen production technologies overview, *J. Power Energy Eng.* 7 (2019) 107–154.
- [8] K.S. Lackner, S. Brennan, J.M. Matter, A.-H.A. Park, A. Wright, B. Van Der Zwaan, The urgency of the development of CO₂ capture from ambient air, *Proc. Natl. Acad. Sci. U.S.A.* 109 (2012) 13156–13162.
- [9] E. Worrell, C. Galitsky, E. Masanet, W. Graus, Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry. An Energy Star Guide for Energy and Plant Managers, Lawrence Berkeley National Laboratory, 2008.
- [10] S.M. El-Beheri, A.A. Hussien, H. Kotb, Mostafa El-Shafie, Performance evaluation of industrial glass furnace regenerator, *Energy* (2016) 1–12.
- [11] V. Sardeshpande, R. Anthony, U.N. Gaitonde, R. Banerjee, Performance analysis for glass furnace regenerator, *Appl. Energy* 88 (12) (2011) 4451–4458.
- [12] R.G. Beerkens, H.P. Muysenberg, H. Barklage-Hilgefort, Modeling of the aging of glass furnace regenerators, *Glastech. Ber.* 65 (9) (1992) 246–255.
- [13] G. Wołkowicki, Experimental results on the fixed matrix regenerator effectiveness for a glass stove furnace, *Heat Tran. Eng.* 37 (6) (2016) 591–602.
- [14] H. Ma, L. Yin, X. Shen, W. Lu, Y. Sun, Y. Zhang, et al., Experimental study on heat pipe assisted heat exchanger used for industrial waste heat recovery, *Appl. Energy* 169 (2016) 177–186.
- [15] R.S. Kaluri, T. Basak, Entropy generation due to natural convection in discretely heated porous square cavities, *Energy* 36 (8) (2011) 5065–5080.
- [16] I. Kotcioglu, S. Caliskan, A. Cansiz, S. Baskaya, Second law analysis and heat transfer in a cross-flow heat exchanger with a new winglet-type vortex generator, *Energy* 35 (9) (2010) 3686–3695.
- [17] A.T. Gheorghian, A. Dobrovicescu, L.G. Popescu, M. Cruceru, B.M. Diaconu, Entropy generation assessment criterion for compact heat transfer surfaces, *Appl. Therm. Eng.* 87 (2015) 137–149.
- [18] Y. Zhou, L. Zhu, J. Yu, Y. Li, Optimization of plate-fin heat exchangers by minimizing specific entropy generation rate, *Int. J. Heat Mass Tran.* 78 (2014) 942–946.
- [19] R. Laskowski, A. Smyk, J. Lewandowski, A. Rusowicz, A. Grzebielec, Selecting the cooling water mass flow rate for a power plant under variable load with entropy generation rate minimization, *Energy* 107 (2016) 725–733.
- [20] M. Bahiraei, S.M. Majd, Prediction of entropy generation for nanofluid flow through a triangular minichannel using neural network, *Adv. Powder Technol.* 27 (2) (2016) 673–683.
- [21] M. Bahiraei, M. Alighardashi, Investigating non-Newtonian nanofluid flow in a narrow annulus based on second law of thermodynamics, *J. Mol. Liq.* 219 (2016) 117–127.
- [22] K. Manjunath, S.C. Kaushik, Second law thermodynamic study of heat exchangers: a review, *Renew. Sustain. Energy Rev.* 40 (2014) 348–374.
- [23] P. Jena, Materials for hydrogen storage: past, present, and future, *J. Phys. Chem. Lett.* 2 (2011) 206–211.
- [24] U. Eberle, M. Felderhoff, F. Schuth, Chemical and physical solutions for hydrogen storage, *Angew. Chem. Int. Ed.* 48 (2009) 6608–6630.
- [25] Z. Zhang, S. Liguori, T.F. Fuerst, J.D. Way, C.A. Wolden, Efficient ammonia decomposition in a catalytic membrane reactor to enable hydrogen storage and utilization, *ACS Sustain. Chem. Eng.* 7 (2019) 5975–5985, <https://doi.org/10.1021/acssuschemeng.8b06065>.
- [26] F. Schuth, R. Palkovits, R. Schlögl, D.S. Su, Ammonia as a possible element in an energy infrastructure: catalysts for ammonia decomposition, *Energy Environ. Sci.* 5 (2012) 6278–6289.
- [27] Yukio Hayakawa, Tomonori Miura, Kota Shizuya, Shintaro Wakazono, Kenya Tokunaga, Shinji Kambara, Hydrogen production system combined with a catalytic reactor and a plasma membrane reactor from ammonia, *Int. J. Hydrogen Energy* 44 (2019) 9987–9993.
- [28] Y. Bicer, I. Dincer, Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles, *Resour. Conserv. Recycl.* 132 (2018) 141–157.
- [29] M. El-Shafie, S. Kambara, Y. Hayakawa, Energy and exergy analysis of hydrogen production from ammonia decomposition systems using non-thermal plasma, *Int. J. Hydrogen Energy* (2020). In Press.
- [30] T. Choudhary, C. Sivadinarayana, D. Goodman, Catalytic ammonia decomposition: CO_x-free hydrogen production for fuel cell applications, *Catal. Lett.* 72 (2001) 197–201.
- [31] A.K. Hill, L. Torrente-Murciano, Low temperature H₂ production from ammonia using ruthenium-based catalysts: synergistic effect of promoter and support, *Appl. Catal., B* 172 (2015) 129–135.
- [32] S. Mukherjee, S.V. Devaguptapu, A. Sviripa, C.R. Lund, G. Wu, Low-temperature ammonia decomposition catalysts for hydrogen generation, *Appl. Catal., B* 226 (2018) 162–181.
- [33] S. Chiuta, R.C. Everson, H. Neomagus, P. van der Grypt, D.G. Bessarabov, Reactor technology options for distributed hydrogen generation via ammonia decomposition: a review, *Int. J. Hydrogen Energy* 38 (2013) 14968–14991.
- [34] S. Satyapal, J. Petrovic, C. Read, G. Thomas, G. Ordaz, The U.S. Department of energy's national hydrogen storage project: progress towards meeting

- hydrogen-powered vehicle requirements, *Catal. Today* 120 (2007) 246–256.
- [35] J.C. Ganley, E. Seebauer, R.I. Masel, Porous anodic alumina microreactors for production of hydrogen from ammonia, *AIChE J.* 50 (2004) 829–834.
- [36] J.C. Ganley, E. Seebauer, R.I. Masel, Development of a microreactor for the production of hydrogen from ammonia, *J. Power Sources* 137 (2004) 53–61.
- [37] A. Bejan, G. Tsatsaronis, M.J. Moran, *Thermal Design and Optimization*, Wiley, 1996.
- [38] G. Tsatsaronis, Strengths and limitations of exergy analysis, in: A. Bejan, E. Mamut (Eds.), *Thermodynamic Optimization of Complex Energy Systems*, Kluwer Academic Publishers, 1999, pp. 93–100.
- [39] D.A. Sama, The use of the second law of thermodynamics in process design, *J. Energy Resour. Technol.* 117 (3) (1995) 179–185.
- [40] M.V. Sorin, V.M. Brodyansky, A method for thermodynamic optimization e l. theory and application to an ammonia-synthesis plant, *Energy* 17 (11) (1992) 1019–1031.
- [41] Z. Kirova-Yordanova, Exergy analysis of industrial ammonia synthesis, *Energy* 29 (12e15) (2004) 2373–2384.
- [42] M. Penkuhn, G. Tsatsaronis, Comparison of different ammonia synthesis loop configurations with the aid of advanced exergy analysis, *Energy* 137 (2017) 854–864.
- [43] J. Szargut, D.R. Morris, F.R. Steward, *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, Hemisphere Publishing, 1988.
- [44] G. Tsatsaronis, Definitions and nomenclature in exergy analysis and exergoeconomics, *Energy* 32 (4) (2007) 249e53, <https://doi.org/10.1016/j.energy.2006.07.002>.
- [45] F. Balkan, N. Colak, A. Hepbasli, Performance evaluation of a triple-effect evaporator with forward feed using exergy analysis, *Int. J. Energy Res.* 29 (2005) 455–470.
- [46] M. Pavelka, V. Klika, P. Vagner, F. Marsík, Generalization of exergy analysis, *Appl. Energy* 137 (2015) 158–172.
- [47] J. Szargut, D.R. Morris, F.R. Steward, *Exergy Analysis of Thermal and Metallurgical Processes*, Hemisphere Publishing Corporation, 1988.
- [48] W. Van Gool, Energy policy: fairly tales and factualities, in: O.D.D. Soares, et al. (Eds.), *Innovation and Technology—Strategies and Policies*, Kluwer, Dordrecht, 1997, pp. 93–105.
- [49] U. Lucia, Mathematical consequences and gyarmatis principal in rational thermodynamics, *Nuovo Cimento B110* (10) (1995) 1227–1235.
- [50] G. Wołkowycski, Experimental results on the fixed matrix regenerator effectiveness for a glass stove furnace, *Heat Tran. Eng.* 37 (6) (2016) 591–602.
- [51] M. Pavelka, V. Klika, P. Vagner, F. Marsík, Generalization of exergy analysis, *Appl. Energy* 137 (2015) 158–172.
- [52] D.A. Sama, The use of the second law of thermodynamics in process design, *J. Energy Resour. Technol.* 117 (3) (1995) 179–185.
- [53] X.-K. Li, W.-J. Ji, J. Zhao, S.-J. Wang, C.-T. Au, Ammonia decomposition over Ru and Ni catalysts supported on fumed SiO₂, MCM-41, and SBA-15, *J. Catal.* 236 (2005) 181–189.
- [54] A.M. Karim, V. Prasad, G. Mpourmpakis, W.W. Lonergan, A.I. Frenkel, J.G. Chen, D.G. Vlachos, Correlating particle size and shape of supported Ru/γ-Al₂O₃ catalysts with NH₃ decomposition activity, *J. Am. Chem. Soc.* 131 (2009) 12230–12239.
- [55] S.S. Stecco, M.J. Moran (Eds.), *A Future for Energy*, Pergamon, Oxford, UK, 1990.
- [56] G. Hammond, Engineering sustainability: thermodynamics, energy systems, and the environment, *Int. J. Energy Res.* 28 (2004) 613–639.