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SIMULATION OF A RECUPERATIVE HEAT EXCHANGER INTEGRATED IN A THERMAL INCINERATOR WITH THE EPSILON-NTU MODEL

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Abstract *Thermal recuperative incinerators are devices commonly used in the industry to control the emissions of organic compounds from the exhaust air of certain industrial process. This is achieved by using these compounds as a comburent in the incinerator and thus both controlling emissions and generating process heat. Thermal recuperative incinerators are designed to efficiently recuperate waste heat from the hot outbound combustion products and preheat the inbound process air. They are usually large and geometrically complex equipment, so modeling an entire thermal recuperative incinerator in detail is difficult. Along with the simulation of the combustion process, another of the challenging aspects is the detailed simulation of the combustion products-to-process gas heat exchanger that encloses the combustion chamber and that promotes heat recovery and thermal insulation of the chamber. One strategy to deal with this challenge is to decouple the simulation of the combustion products-to-process air heat exchanger from the simulation of the combustion chamber. By doing so, the amount of heat transfer from the combustion products to the inbound process air can be determined and imposed as a boundary condition for the simulation of the combustion chamber. This work presents a simple mathematical model for describing the combustion products-to-process air heat exchanger integrated in a TRI used in a paint shop of an automotive assembly plant. The model relies on the well-established effectiveness method for modeling heat exchangers, the ε-NTU method. The results obtained in this work are validated using experimental data obtained in an industrial environment.*

1. INTRODUCTION

The growing concern over environmental pollution and the need to efficiently manage waste has led to the development of various technologies for waste management, including thermal recuperative incinerators. These incinerators are designed to burn solid, liquid, or gaseous waste in a controlled environment to reduce their volume and eliminate harmful contaminants [1]. One critical component of thermal recuperative incinerators is the heat exchanger, which is used to recover heat from the hot combustion gases and transfer it to the incoming fuel or to the colder contaminated air. This preheating process improves the incinerator efficiency by reducing the fuel needed to maintain the temperature required for the incineration.
The present work aims to simulate an industrial Volatile Organic Compound (VOC) thermal recuperative incinerator using classical thermodynamics, and heat transfer and heat exchanger theory. Modelling heat exchangers with complex geometries and when the three modes of heat transfer are relevant requires the knowledge of classical heat transfer theory, which provides a wider framework for understanding and predicting the heat transfer in complex physical systems. In the heat exchanger theory, the Effectiveness-Number of Transfer Units (ϵ-NTU) model is a widely used method and a valuable tool for analysing the performance of heat exchangers [2-8]. It can be used to analyse and optimize the design of thermal recuperative incinerators. The method is based on two parameters: the heat exchanger effectiveness, which measures the ratio of the actual heat transfer to the maximum possible heat transfer, and the number of transfer units (NTU), which measures the heat exchanger size. The ϵ-NTU model can predict the performance of different heat exchangers, including cross-flow, counter-flow, and parallel-flow heat exchangers. This method was used in the present work, along with the first law of thermodynamics and the equations that express mass conservation and heat transfer by conduction, convection and radiation [2, 3]. As the world continues to grapple with the challenge of waste management, technologies like thermal recuperative incinerators will play a vital role in reducing the impact of waste on the environment, and heat exchangers will continue to be an essential component of these systems.

2. METHOD

2.1. Thermal recuperative incinerator

The thermal recuperative incinerator studied in this work is one of the equipment associated with a paint-shop oven of a vehicle assembly plant located in the European Union. This incinerator has a complex geometry, which includes a heat exchanger with a challenging thermodynamic concept (Figure 1). The cylindrical combustion chamber is at the core of the incinerator. It comprises a burner and, at the outlet, a fork-point to the heat exchanger and the incinerator exhaust. Surrounding the CC, the heat exchanger has two regions: a jacket wrapped around a cylindrical combustion chamber (CC) and an annular enclosure containing a tube bundle. The jacket outer wall is concentric with the CC wall and is also the inner wall of the casing that encloses the tube bundle. The jacket inner wall separates it from the CC. The tube bundle is located around the combustion chamber, and is comprised of hundreds of tubes with their centres disposed in two concentric cylinders radially separated. The jacket has a direct connection with the inlet of the tubes and the outlet of the CC, while the tubes are directly connected to the jacket and the incinerator exhaust outlet. The outer layer of the thermal recuperative incinerator is made of an isolating material.

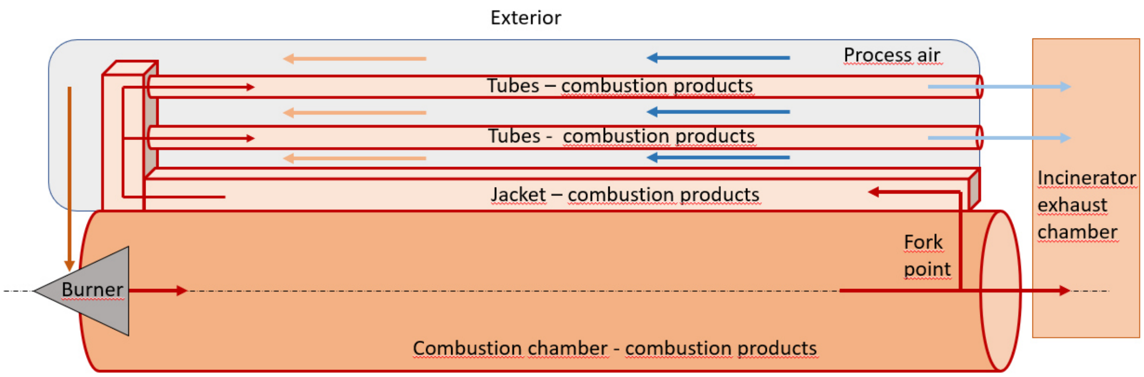

Figure 1. Sketch of the thermal recuperative incinerator studied.

Thermodynamically, the process air that enters the incinerator coming from the paint-shop oven is of particular interest. This fluid is preheated by the combustion products both flowing inside the tube bundle and through the jacket, and then goes to the burner where it reacts with natural gas. This preheating of the combustion air raises the combustion efficiency, which results in less fuel consumption. However, to provide such preheat capabilities, there is a complex coupled system consisting of a burner, a combustion chamber with a fork-point at the end, which will split the flow in two different directions; one to the jacket and the other to the incinerator exhaust. The flow that goes to the jacket will transport all the energy to be exchanged at the jacket and tube bundles.

Providing a full description of the flow path will enhance the understanding of the heat transfer involved in the process. Figure 1 gives insight into the pathway of the gases inside the incinerator. As the colder process air coming from the paint-shop oven enters the incinerator, it will follow through the annular enclosure that contains the tube bundle and exchange thermal energy with the combustion chamber jacket and the tubes. When leaving the heat exchange zone, the preheated air will react with the fuel at the burner and raise the temperature of the combustion compared to the case where no preheating occurred. The combustion product flow will split at the end of the combustion chamber; one part goes into the heat exchanger and the other directly into the incinerator exhaust chamber. The combustion gases that are directed to the heat exchanger transfer heat to the air coming from the oven first through the combustion chamber jacket, secondly through the tubes. After passing through the jacket and tubes, the combustion products will follow to the incinerator exhaust chamber to be mixed with the fraction of the combustion products that do not pass through the heat exchanger before leaving the thermal recuperative incinerator.

2.2. Mathematical model

The heat transfer from the hot combustion products to the colder air coming from the paint-shop oven is described by a mathematical model based on the Effectiveness-Number of Transfer Units (ε-NTU) method, which is well-established to evaluate heat exchangers where the outlet temperatures are unknown. The ε-NTU method is described, for example, in [2-8].

For the ε-NTU analysis performed in this work, the heat exchanger is divided into two smaller systems: *i*) one where heat is transferred from the combustion products that flow in the jacket to the air coming from the oven and *ii*) another where heat is transferred from the combustion products that flow inside the tubes to the air coming from the oven. The heat transfer through the jacket wall is described as in a co-current (parallel) heat exchanger with the hot fluid flowing in an inner annulus and the cold fluid in an outer tube. On the other hand, the heat transfer through the tube walls is described as in a counter flow heat exchanger.

The equations that describe the heat transfer from the combustion chamber to the jacket and from the air coming from the paint-oven to the exterior are the general heat transfer equation that account for conduction, convection (forced or natural), and radiation [2-8].

The system of equations used to simulate the thermal recuperative incinerator is complete with three energy conservation equations written for: *i*) the combustion zone, *ii*) the combustion products flowing through the jacket and *iii*) the air that flows through the annular enclosure that contains the tube bundle.

An iterative approach is used to solve the system of equations that describe the thermal recuperative incinerator. The needed inputs are known from measurement data *in situ*. These are the temperatures and mass flow rates of both the fuel and the process air coming from the paint-shop oven. Also measured are the temperature of the combustion products at the end of the combustion chamber and at the outlet of the incinerator. However, there are no measurements of the temperatures at the inlet of the burner nor at the end of the tubes, and no measurement of the airflow split at the end of the combustion chamber. The latter is needed as input to solve the system of equation. The approach used in this study was to calculate the unknown temperatures, the heat transfer rate through the walls and the system overall efficiency as a function of the fraction of the flow directly exhausted to the incinerator mixing chamber, i.e., the fraction of the flow that does not pass through the heat exchanger.

3. RESULTS

Figure 2 represents, as a function of the percentage of combustion products that flow directly to the exhaust, the heat transfer rate from the combustion chamber to the jacket (Q_{cc}), from the jacket to the annular enclosure containing the tube bundles (Q_{jacket}), from the tubes to the annular enclosure (Q_{tubes}) and from the thermal recuperative heat exchanger to the surroundings (Q_{exterior}). The highest heat transfer rates occur when the percentage of combustion products that pass through the heat exchanger is the highest. In this case, more heat from the combustion product stream is recovered and the flame temperature is the highest. As the direct flow of combustion products to the exhaust increases (heat exchanger flow decreases), the preheating of the air coming from paint-shop oven decreases and so does the combustion temperatures and the heat lost by the combustion chamber. When around 60% of the flow passes directly to the exhaust, the heat transfer rates increase because the flow regime in the tubes changes from transitional to laminar. The change that happens at the tubes is reflected throughout the entire system.

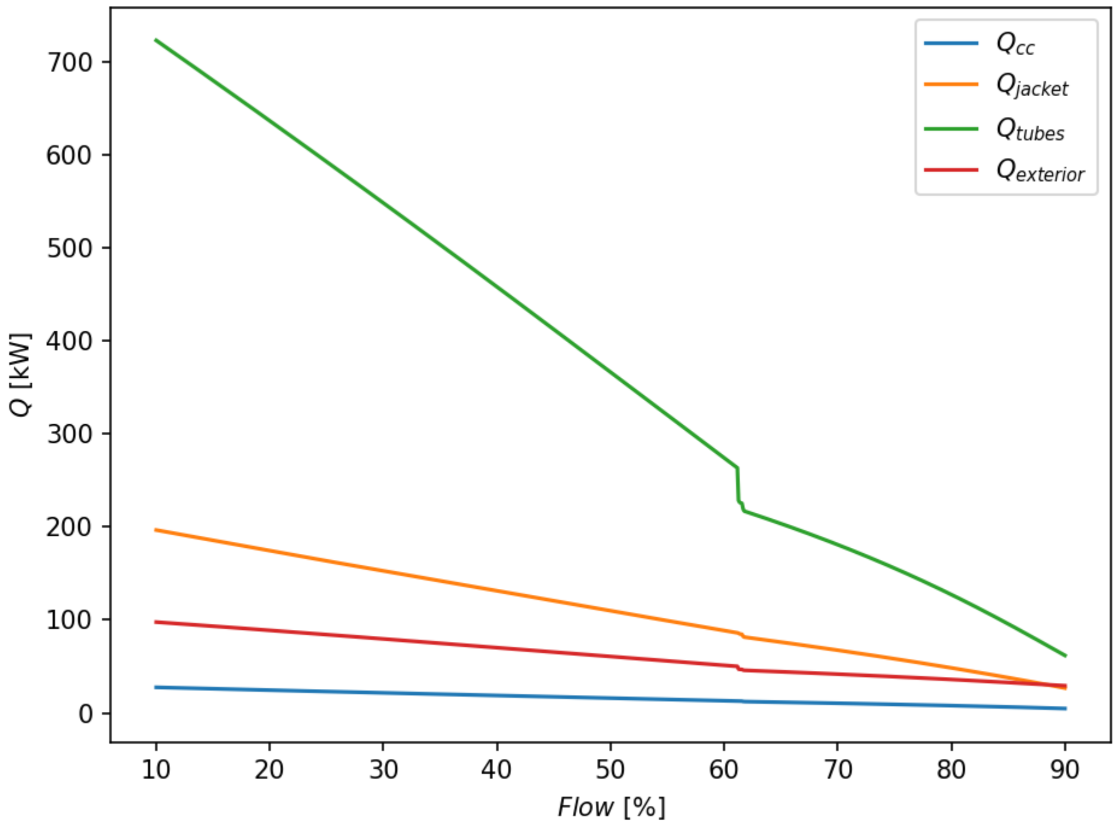

Figure 2. Heat transfer rates in the thermal recuperative incinerator.

Figure 3 shows the thermal efficiency of the incinerator from the point of view of the heat gained by the process air coming from the paint-shop oven. This efficiency is defined as the ratio of the amount of heat generated with heat recovery and without heat recovery. The results show that when more mass flow rate passes through the heat exchanger than directly to the exhaust, the efficiency is higher than when most of the flow is directed to the exhaust. For high percentages of combustion products that flow directly to the exhaust, the thermal efficiency of the incinerator approaches 1, showing no heat recovery.

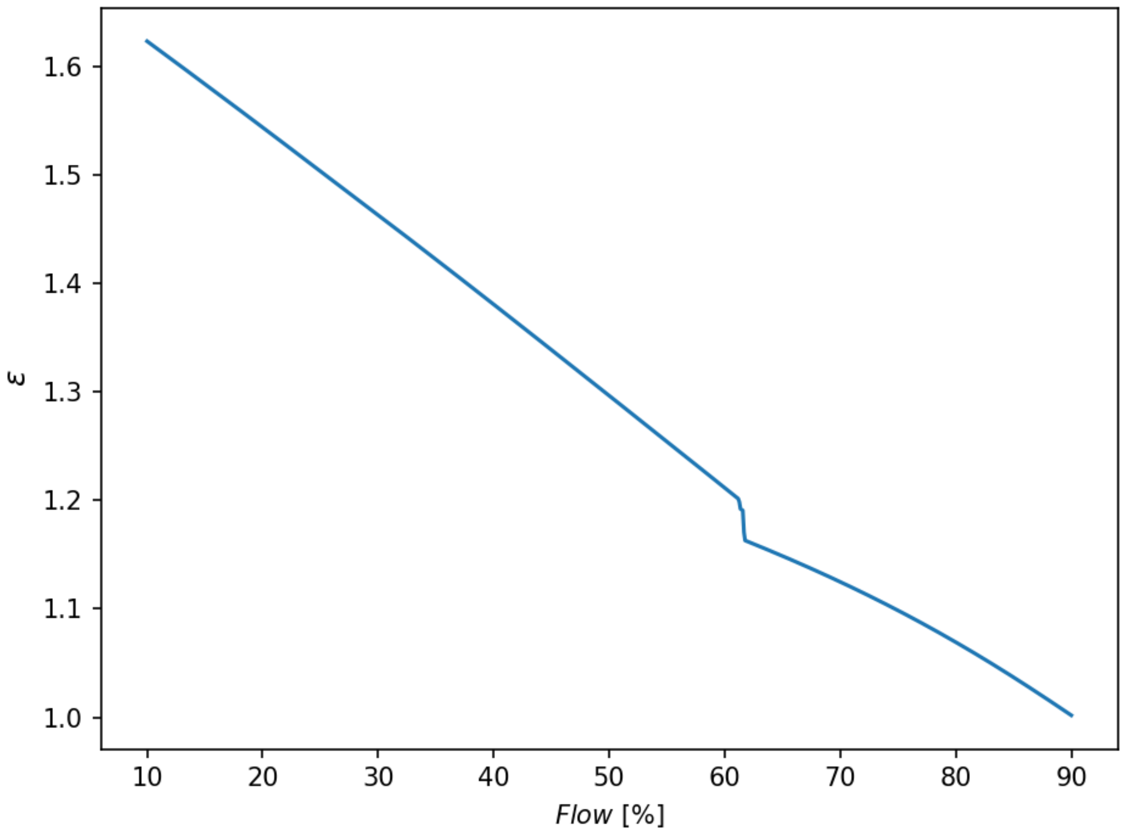

Figure 3. Thermal efficiency of the incinerator.

Figure 4 shows the fluid temperature difference between the inlet and outlet of the combustion chamber (ΔT_{cc}), of the jacket (ΔT_{jacket}), of the tube bundle (ΔT_{tubes}) and of the enclosure that contains the tube bundle ((ΔT_{air}). This parameter is an indicator of the thermal energy available along the process. Following the CC line, which shows how the CC feeds the whole system by keeping the energy available almost constantly along the process, the same for the jacket line which benefits of being fed directly by the CC. At this point, the jacket not only releases energy to the air but it receives energy from the combustion chamber, that keeps the temperature at the jacket inlet high while the flow to the heat exchanger decreases. The air enters the tubes bundle and suffers the biggest exchange of energy of all systems with the air, besides being the biggest exchanger, it ranges from the transition flow regime to the laminar which shows a deterioration as the flow becomes laminar which lowers the energy available and deteriorate the overall heat transfer system. It is possible to state this by looking at the air line which is the main indicator of the heat exchanger system.

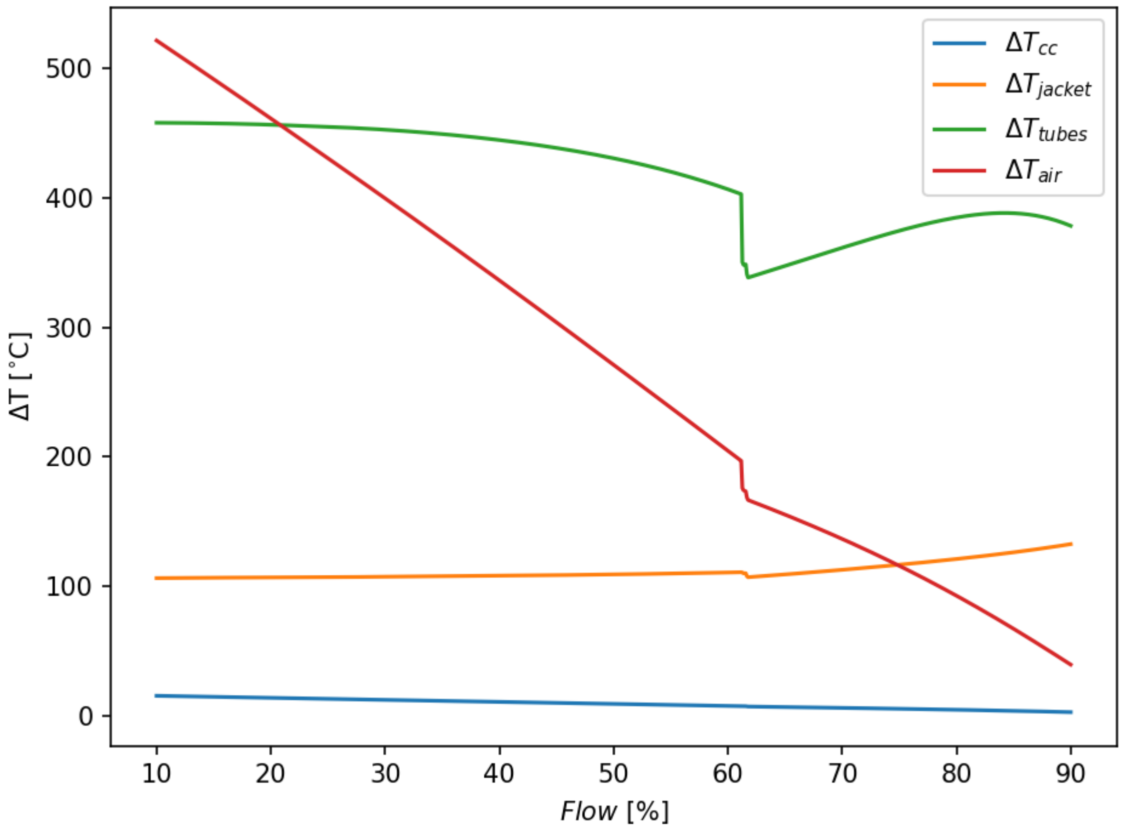

Figure 4. Temperature differences.

The results obtained from this study are presented as a function of the percentage of the mass flow rate directly exhausted to the incinerator mixing chamber. The thermal recuperative incinerator is being monitored, which makes it possible to know crucial operation measurements of the process and helps us understand how reasonable the model is.

5. CONCLUSIONS

The heat recovery system of the incinerator is of extreme importance to lower the consumption of fuel. Within the working range, around 17% can be saved. There are interesting behaviours about the fork point flow management, as it brings counterintuitive thoughts about the heat transfer inside the incinerator. However, the system is highly dependent on the initial conditions, and the combinations of initial conditions with the fork point are very sensitive. The flow regime is a crucial factor due to its ability to deteriorate the overall efficiency of the incinerator. The model needs improvement on the combustion calculations, the radiation heat transfer, the correlations for the transitional regime, and the numerical methods used to solve the complex physical behaviour. There is room for the development of thermodynamics optimizations as this work is an ongoing process.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Salvador, S., Commandre, J.M., Kara, Y. “Thermal recuperative incineration of VOCs: CFD modelling and experimental validation”, *Applied Thermal Engineering*, Vol. 26(17-18), pp. 2355-2366, 2006.
[2] Cengel, Y.A., Ghajar, A.J., *Heat and Mass Transfer: Fundamentals & Applications*, 2011.
[3] Bergman, T.L., Bergman, T.L., Incropera, F.P., Dewitt, D.P., Lavine, A.S., *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, 2011.
[4] White, F.M. *Fluid Mechanics*, 2017.
[5] Lestina, T., Serth, R.W., *Process Heat Transfer: Principles, Applications and Rules of Thumb*, 2014.
[6] Sinnott, R.A., *Chemical Engineering Design*, Elsevier, 2014.
[7] Chen, L.Y., Adi, V.S., Laxmidewi, R. “Shell and tube heat exchanger flexible design strategy for process operability”, *Case Studies in Thermal Engineering*, Vol. 37, pp. 102163, 2022.
[8] Shah, R.K., Sekulic, D.P., *Fundamentals of Heat Exchanger Design*, John Wiley & Sons, 2003.