Project Report
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Predicting performance of regenerative heat exchanger

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ABSTRACT
One way to improve the efficiency of a power plant is to preheat the air intake with heat from the exhaust gas. When the intake of air is preheated less energy from the fuel are needed to keep a high temperature in the chamber, which result in a higher efficiency of the plant. A typical way to preheat the air intake is to use a regenerative heat exchanger between the air intake and the exhaust gas. The exactness of the heat transmission calculation would provide a good base how to exactly regulate the flows of every fluid, saving pumping cost, optimizing efficiency and decreasing the maintenance. To predict the behavior of the heat transfer in this heat exchanger is therefor an important issue. [1]

NOMENCLATURE

A	surface area of control volumes at active site, m^2
C	heat capacity rate, J/(s·K)
C_r	matrix wall heat capacity
$\overline{C}$	heat capacitance, kg ·J/(kg·K)
h	heat transfer coefficient, W/(m^2·K)
L	length of the matrix, m
N	revelation speed, s^{-1}
q	heat flow, J/s
T	temperature, K

Greek Symbols

θ	angel, rad
τ_d	fluid dwell time, s

Subscripts

c	cold
h	hot
i	conditions at the inlet
o	conditions at the outlet
r	regenerator
t	total period, cold- and hot- period, and the time between that.
w	wall

Superscripts

x, τ	are used as coordinate system.

INTRODUCTION
Rotating regenerative heat exchangers consist of a heat storing matrix with a lot of canals where a fluid can be passing through and exchange heat energy with the matrix. The hot gas is passing through at one side of the matrix and the cold gas at the other side of the matrix. The matrix is continuously rotating at a low speed. The side of the matrix that has been heated up by the hot gas can after shifting side provide the cold gas with heat. (There are also models where the matrix is fix and the cold- and hot gas is shifting side). Figure 1.a. shows the basic principles. Traditionally the heat transfer process in regenerative heat exchanger, have been described by dimensionless groups combined with table values. Today, attempt have been done to find numerical solutions that in a general way better describe the heat transfer process with higher accuracy. Both methods can be derived from the same origin.[2]

Generally, the advantages of a regenerator over a recuperating heat exchanger is that it has a much higher surface area for a given volume, which provides a reduced exchanger volume for a given energy density, effectiveness and pressure drop. This makes a regenerator more economical in terms of materials and manufacturing, compared to an equivalent recuperator. Furthermore, flow sectors for hot- and cold fluids in rotary regenerators can be designed to optimize pressure drop in the fluids. The matrix surfaces of regenerators also have some degree self-cleaning characteristics, reducing fluid-side fouling and corrosion. Finally, properties small as surface density and counter-flow arrangement of regenerators make it ideal for gas-gas heat exchange applications requiring effectiveness exceeding 85%. The heat transfer coefficient is much lower for gases than for liquids, thus the enormous surface area in a regenerator greatly increases heat transfer. The greatest disadvatnages with regenerating heat exchangers is that it's not possible to hold the two gases apart, and therefore there will always be a small leacage between the two gases. But in the applications where regenerative heat exchangers are used to preheat the air with heat from the exhaust gas, the impact of this mixing of the fluids is generally little.[3]

The purpose of this project report is to give a brief summary over the heat transfer process that occurs in the regerative heat exchangers, and how to make calculations to predict their behavior.

THE HEAT TRANSFER PROCESS

There are a lot of variables that impact the heat transfer process that can't be put aside, if one should get an accurate description of the process. The roughness of the surface, real dimensions, porosity etc. are variables that are difficult to measure and which have a great impact on the heat exchanger performance. These variables that are mentioned above vary over time and can not totally be predicted.

The impact of the exhaust gas on the performance is one of the main reasons why it is hard to predict the heat transfer process over time. The smoke can transport slag, and other solid particles with high adherence. Even the standard emission that isn't solid particles can be hard to predict, and they will also have a big impact on performance. In a biomass-fired, but also in fossil-fuel power plant, the content of the fuel could change a lot. Oxidation and material deposition have a big impact for changing the conductivity of the heat exchanger. In some degree this could be arranged by cleaning equipment within some intervals, but this may also demand other efforts on the power plant.

It is well known that one way to protect the equipment of corrosion is to control the lowest temperature. Low temperature corrosion occurs at a temperature lower than a certain level. When the load on the plant is low, then the temperature on the metal is lower which result in greater deposition of slag.

The control of the temperature at the matrix is normally done by using a bypass on the input air, recycling parts of the hot air or using hot steam. At some level, the temperature could be controlled by controlling the rotating speed, but it is not enough protection since slow main flow do not warrant high local speed. [2]

In almost every heat exchanger there are two main physical processes that are occurring: pressure losses and temperature transmission. In regenerative heat exchanger there are also mass exchanges if phase changes of more than one components of the two fluid streams occur within the thermodynamic operating condition. Low temperature corrosion is a direct phenomenon of phase change. There are two possible mass transfer mechanisms that can occur in the heat exchanger: condensation/evaporation and sorption/desorption. Both mechanisms are described with the same differential equation, but with different thermodynamic relationship. [4]

The heat transference process in a rotating heat exchanger, which is used for preheating, can be considered as a combination of conduction, convection and radiation. Some of the gases within the emissions from the exhaust gas, mainly CO_2 and H_2O, have important radiation properties. Therefore this type of heat transfer can not be disregarded from the exhaust gas. The emissivity of the gas changes with temperature and then with existence of other mixed gases, and total flows are functions of the radiating surface. The capacity of transference is also related to the storing properties of material, and it obviously depends upon its own conductivity. Since there will be a thin film on the surface with poor characteristic within the matrix, the conductivity will not be uniform. The thickness of the film and its degree of coherence will have a great importance of the global performance of the heat exchanger. The conductivity in gases is strongly dependent on the temperature, so the temperature and the type of gas have to be introduced when modeling. The values of the coefficient change over time, and they will also change when different fuels are used in varying proportions. The next main physical process, namely the pressure losses is partly an consequence of the changes in temperature, but also from the sealing and the inner resisters of the matrix. [1]

PROBLEM STATEMENT

As have been explained under the previous topics there are a lot of facts that may affect the heat transfer process and which are desirable to have in consideration. Usually the following assumptions are made when calculating or analyzing the heat transfer process:

- The regenerator operates under quasi-steady-state or regular periodic-flow conditions (i.e., having constant mass flow rates and inlet temperatures of both fluids during respective flow periods).
- Heat loss to or heat gain from the surroundings is negligible (i.e., the regenerator outside walls are adiabatic).
- There are no thermal energy sources or sink within the regenerator walls or fluids.
- No phase change occurs in the regenerator.
- The velocity and temperature of each fluid at inlet are uniform over the flow cross section and constant with time.
- The analysis is based on average and thus constant fluid velocities and the thermophysical properties of both fluids and matrix wall material throughout the regenerator (i.e., independent on time and position).
- The heat transfer coefficients (h_h och h_c) between the fluids and the matrix wall are constant (with position, temperature, and time) throughout the exchanger.
- Longitudinal heat conduction in the wall and the fluids is negligible.
- The temperature across the wall thickness is uniform at a cross section and the wall thermal resistance is treated as zero for transverse conduction in the matrix wall (in the wall thickness direction).
- No flow leakage and flow bypassing of eater of the two fluids streams occurs in the regenerator due to their pressure differences. No fluid carryover leakage (of one fluid stream to the other fluid stream) occurs of the fluids trapped in flow passages during the switch from hot to cold fluid period, and vice versa, during matrix rotation or valve switching.
- The surface area of the matrix as well as the rotor mass is uniformly distributed.
- The time required to switch the regenerator from hot to cold gas flow is negligibly small.

- Heat transfer caused by radiation within the porous matrix is negligible compared with the convective heat transfer.
- Gas residence (dwell) time in the matrix is negligible relative to the flow period.

LITERATURE SURVEY

The conventional theory about calculating the heat transfer process in rotating regenerative heat exchanger are derive from the theory that H. Hausen presented in *Über die Theorie des Wärmeaustauches in Regeneratoren*, in the beginning of the 1930' [5]. Other persons that have had a big influence over the development of the theory within this subject are: Nusselt, Schumann, Jakob, Eckert and Drake. There are also some other persons that have published different reports that in some way cover same topics. These reports have been published every now and then since Hausen got his break throw. Today's computational capacity has made it reasonable to search for analytical solutions that is far more advanced with higher accuracy and that takes more variables in consideration. Over the past couple of years, there have been published a smaller amount of reports within the subject; many of them with different numerical solution that has been done on different experiments.

PROJECT DESCRIPTION

With the assistance of figure 1 and figure 2 it is possible to derive the governing equations and the boundary conditions. In the following derivation the assumptions that is mentioned under the topic *project statement* are included.

Hot period, Fluid. Figure 2.a. shows the differential fluid and matrix elements of the hot-gas flow period, with the associated energy transfer terms. During the flow through the elemental passage the hot gas transfer heat to the walls of the matrix by convection, which result in reduction of the outlet enthalpy, and in an internal energy storage. This is shown in figure 2.a. By applying an energy balance the following equation arrive:

$$C_h T_h - C_h\left(T_h + \frac{\partial T_h}{\partial x}dx\right) - h_h\frac{A_h dx}{L}\left(T_h - T_{w,h}\right) = \bar{C}_h\frac{dx}{L}\frac{\partial T_h}{\partial \tau_h}$$

By substituting with the value of $\bar{C}_h = C_h\tau_{d,h}$ and simplifying, the following equation occurs:

$$\frac{\partial T_h}{\partial \tau_h} + \frac{L}{\tau_{d,h}}\frac{\partial T_h}{\partial x} = \frac{(hA)_h}{C_h\tau_{d,h}}\left(T_{w,h} - T_h\right)$$

Hot Period, Matrix. With the following assumption of constant angular velocity, zero longitudinal and infinite transverse wall heat conduction, - all the heat transferred from the hot fluid to the matrix wall is stored in the wall which result in an increased enthalpy in the wall. Combined with an energy balance over the matrix wall in figure 2.b. result in the following equation:

$$\left(\bar{C}_{r,h}\frac{dx}{L}\right)\frac{\partial T_{w,h}}{\partial \tau_h} = h_h\frac{A_h dx}{L}\left(T_h - T_{w,h}\right)$$

By combining the equation above with the knowledge that $C_{r,h}\theta_h = \bar{C}_{r,h}$ and then simplifying the both of them, you'll get:

$$\frac{\partial T_{w,h}}{\partial \tau_h} = \frac{(hA)_h}{C_{r,h}\theta_h}\left(T_h - T_{w,h}\right)$$

Cold period: Fluid and matrix: For the cold period, a pair of equations similar to those which have been used above, combined with energy balance will lead to the following equations:

$$-\frac{\partial T_c}{\partial \tau_c} + \frac{L}{\tau_{d,c}}\frac{\partial T_c}{\partial x} = \frac{(hA)_c}{C_c\tau_{d,c}}\left(T_c - T_{w,c}\right)$$

$$-\frac{\partial T_w}{\partial \tau_c} = \frac{(hA)_c}{C_{r,c}\theta_c}\left(T_{w,c} - T_c\right)$$

The boundary conditions are according to the previous assumptions. The inlet temperature of the hot gas is constant during the hot-gas flow period, and the inlet temperature of the cold gas is constant during the cold-gas flow period:

$T_h(0,\tau_h) = T_{h,i} =$ constant for $0 \le \tau_h \le \theta_h$

$T_c(L,\tau_c) = T_{c,i} =$ constant for $0 \le \tau_c \le \theta_c$

The periodic equilibrium conditions for the walls are:

$T_{w,h}(x,\tau_h = \theta_h) = T_{w,c}(x,\tau_c = 0)$ for $0 \le x \le L$

$T_{w,h}(x,\tau_h = 0) = T_{w,c}(x,\tau_c = \theta_c)$ for $0 \le x \le L$

Since the regenerator is in periodic equilibrium, the boundary condition mentioned above are also valid for $\tau = \tau + n\theta_t$, where n is an integer, n≥0. The corresponding analytical models can be solved using analytical and semi-numerical methods. In applications where the hot- and/or cold-fluid inlets to the regenerator have non-uniform temperature profiles, the solution can be obtained by a numerical analysis.

Based on the foregoing differential equations and boundary conditions, the dependent fluid and matrix temperatures are functions of the following variables and parameters:

$$T_h, T_c, T_w = \phi\left[x, \tau_h, \tau_c, \quad T_{h,i}, T_{c,i}, C_h, C_c, \tau_{d,h}, \tau_{d,c}, \quad C_r, (hA)_h, (hA)_c, L, \theta_h, \theta_c\right]$$

Where the first three terms from the left are dependent variables, the next three are independent variables, the next six are operating condition variables, and the last six are parameters under designer's control.

Neither $C_{r,c}$ nor $C_{r,h}$ is included in the forgoing list since it can be shown that $C_{r,c}$=$C_{r,c}$=C_r.

The regenerator fluid and wall temperatures are thus dependent on 15 independent variables and parameters.

Through non-dimensionalization it is possible to obtain four independent and one dependent dimensionless group. Two sets of dimensionless groups have traditionally been used for regenerator analysis leading to two design methods. The effectiveness-number of transfer units (ε-NTU_0) method is generally used for rotary regenerators. The reduced length-reduced period (Λ-π) method is generally used for fixed-matrix regenerators. It has been shown that both methods are equivalent. [2]

Within each method there are a couple of corrections methods that takes into account that some of the assumptions are too rough. But the most accurate method seems to be the numerical analysis but it's also the most demanding method since it needs a deep-going analysis of all constants. [1,2,6]

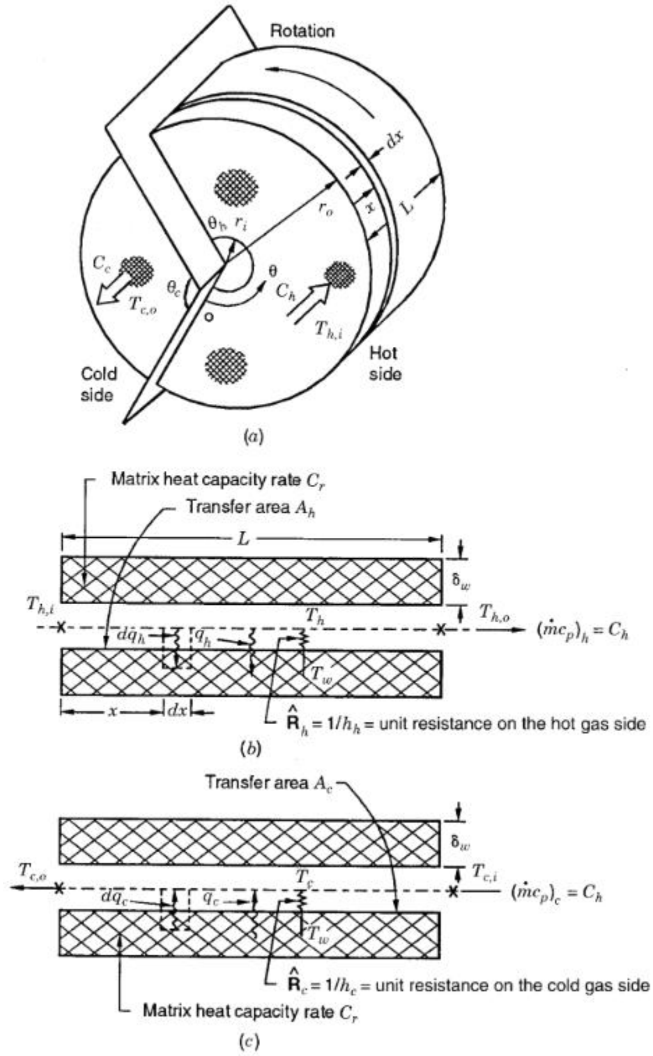

Figure 1; (a) Rotary regenerator showing sections *x* and *dx*; (b) regenerator elemental flow passage and associated matrix during the hot-gas flow period; (c) same as (b) during the cold-gas flow period. [2]

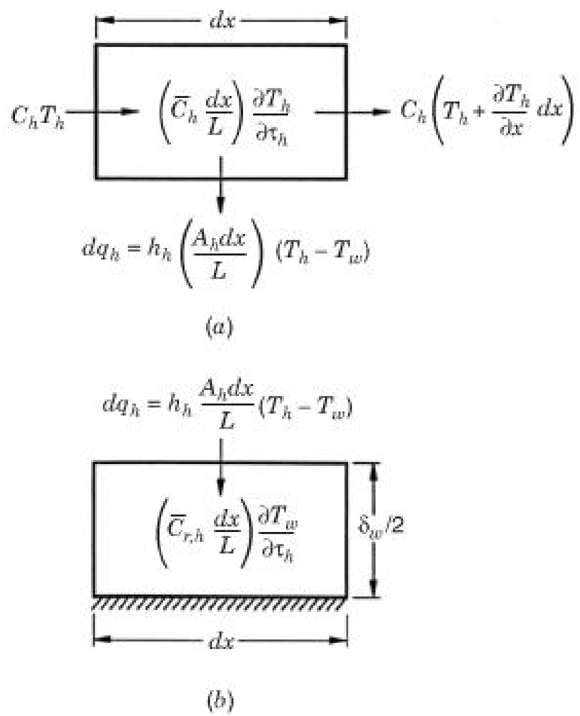

Figure 2; Energy rate terms associated with the elemental passage *dx* (a) of fluid, and (b) of matrix at a given instant of time during the hot-gas flow period. [2]

CONCLUSIONS

The heat transfer process in a regenerative heat exchanger that work between the intake of air and the exhaust gas in a power plant is very complex. In fact, it is not possible to make any analytical solution that describes the process. It is also very hard to find a numerical solution with a high accuracy that considers all those facts that have a high influence of the result. [1]

Essential relations that are needed for further analysis has also been shown in this project report. Where focus have been on the energy equations.

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