Thermal Impedance − Basis of the Regenerator Theory

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Abstract

In this brief report, the analysis of the heat exchanger-regenerator theory is carried out on the basis of a new thermophysical concept − thermal impedance, which allowed us to give a new interpretation of the heat transfer process and a fundamentally different method of thermal calculation periodic heat transfer in it.

Keyword - *heat exchanger-regenerator, electrothermal analogy, thermal impedance, complex thermal resistance, active and reactive resistance.*

I. INTRODUCTION

The development of an accurate theory of heat exchangers-regenerators is a task of transcendental difficulty, which has not yet been completed. Therefore, in this case, the following approach seems appropriate: a mathematical model of the heat transfer process should be found by a qualitative solution, i.e. first get a closed analytical solution of the heat transfer problem in a simplified formulation. This will then allow not only to clarify it, but to formulate and accurately solve the problems of thermal calculation of the regenerator by numerical methods, while being able to correctly interpret the results of numerical calculation.

The author of [1] presented some preliminary results of an analytical solution of the problem with “lumped parameters”, which allowed finding out the physics of the heat transfer process and finding the mathematical apparatus organically inherent in this problem, in the very structure of which some conditions are included which are additionally involved in the existing approaches. Thus, for example, the use of Fourier series in this analysis allowed us to exclude from the formulation of the problem the so-called “switching condition” of Hausen [2], which determines the continuity of the temperature schedule of the packing (switching line).

II. METHODS

As a result of this decision, it was found that since the heat transfer in the regenerator is due to periodic fluctuations in the temperature of both media washing the nozzle, and its thermal circuit contains heat capacity C (m·c), according to the electrothermal analogy, the thermal resistance of this circuit is complex and includes in addition to the active component R, the reactive component X is also, and the mathematical apparatus corresponding to the physics of the heat transfer process in the regenerator is a complex calculus device.

The complex thermal resistance of the regenerator thermal circuit (its thermal impedance is Z) is expressed by the corresponding radius - vector on the complex plane ($Z = R + iX$, where i is the imaginary unit, $i = \sqrt{-1}$) and is analogous to the electrical impedance for the variable a current containing capacitance known as a capacitor [3].

The presence of a reactive component in the thermal resistance of the regenerator thermal circuit determines the presence of an appropriate “phase shift” angle between temperature fluctuations of the environments washing the nozzle (square wave) and temperature fluctuations of the nozzle (switching line), which is the cause of the “temperature hysteresis loop” on switching lines.

III. RESULTS

As a result of analyzing the physics of the periodic heat transfer, it was found that the resulting heat flux Q in the regenerator is determined by the module of the complex thermal resistance $Z = R + iX$ ($Z = |Z| = \sqrt{[R^2 + X^2]}$). Thus, the transmitted heat Q is inversely proportional to the square root of the sum of the squares of the components of Z (active R and reactive X), and not their arithmetic sum, as it is now decided to define, for example, in the framework of the Rummel semi-empirical formula [4]. I have a regenerator in a circuit with “lumped parameters”, obtained by the operational method: $Z = R/th(X/R)$, given in [2].

The active component R of total thermal resistance (scalar Z) for regenerators with a quasi-isothermal packing (provided that the number of Bio attachments is small ($Bi \to 0$) is typical for Yungstrom regenerators (Fig.1) with a packing in the form of a package of metal sheets determined by the Nusselt formula: $1/R_j = W_j \cdot [1 - exp(-Ntu_j)]$, where W is the so-called “water equivalent” of coolant flows (“hot” and “cold”, with $R = R_h + R_c$, and $W_h = W_c$), Ntu − is the so-called number of "units of transport" ($Ntu_h = Ntu_c = \alpha F/W$).

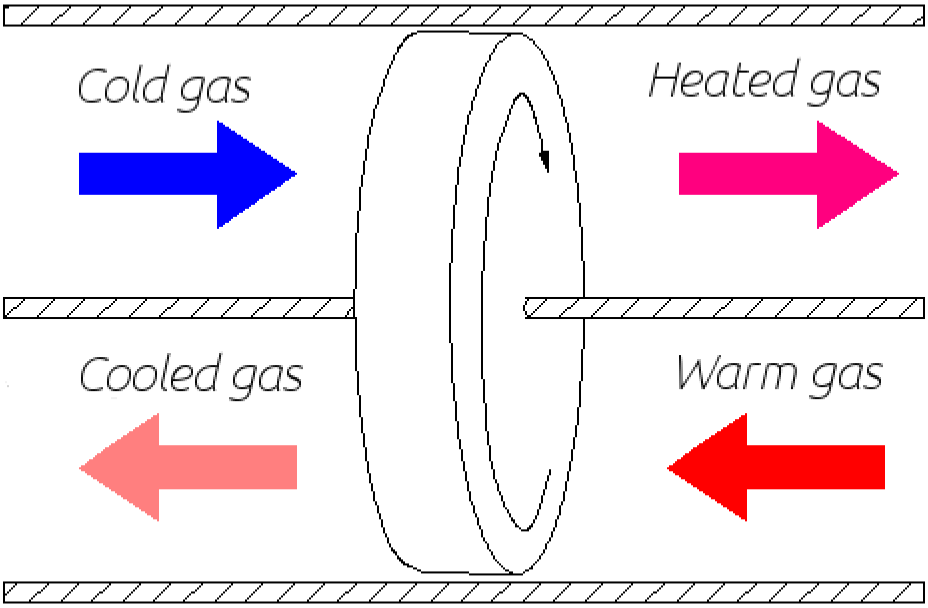

Fig.1. Scheme of heat exchanger-regenerator Jungstrem

The reactive component X of the total thermal resistance Z of such regenerators is determined by the formula: 1/X = ω·C*, where ω is the switching frequency, and C* is the reduced heat capacity of the regenerator nozzle, it turned out to be 22.5% more than its actual value C (C = c·m), which is caused by the non-harmonic form of temperature fluctuations (and oscillations of the media washing the nozzle and the nozzle itself), which are given to both the shape of the meander and the switching line, respectively.

IV. CONCLUSION

Thus, in this work the theory of a heat exchanger - regenerator was for the first time based on a new thermophysical concept thermal impedance, which made it possible to give a new interpretation of the heat transfer process and a method of its thermal calculation that differs fundamentally in the world.

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