Thermal stress in a ceramic brick air preheater

by Rodney Carl Harris

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
Thermal stresses were calculated for an experimental magnetohydrodynamic cored ceramic brick regenerative air preheater. The finite element method was employed for determining both temperature and stress distributions for individual ceramic core bricks at typical cyclic equilibrium operating conditions. Maximum stress values and their locations in the hexagonal core bricks were calculated and compared with values predicted by an earlier, more approximate method as well as with failure modes in an actual preheater. The maximum stresses were found to be circumferential; that is, acting perpendicularly to the direction of the gas flow passages.

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Signature Rodney Carl Harris

Date Sept 19 1978

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NOMENCLATURE

Symbol	Description
a	flow hole radius
b	equivalent flow hole outer radius
D	flow hole diameter
E	ceramic Young's Modulus
EOB	end of blowdown
EOR	end of reheat
F_{i-j}	shape factor from surface i to surface j
f	Darcy-Weisbach friction factor
f_o	Darcy-Weisbach friction factor for smooth pipe
f_r	Darcy-Weisbach friction factor for rough pipe
g	acceleration of gravity
Gr_{δ}	perimeter gap Grashof number
h_c	brick perimeter convective coefficient
h_f	flow hole convective coefficient
h_r	brick perimeter equivalent radiative coefficient
h_T	brick perimeter total convective coefficient
k_c	ceramic thermal conductivity
k_g	flow hole gas thermal conductivity
k_{g_p}	perimeter gap gas thermal conductivity
k_s	flow hole equivalent sand grain roughness
N	number of radiative surfaces

Symbol	Description
Nu	flow hole local Nusselt number
Nu_{δ}	perimeter gap Nusselt number
Pr	flow hole local Prandtl number
Q	heat flux at flow hole surface (Upshaw)
q_f	heat flux at flow hole surface
q_i	radiant heat flux at surface i
q_w	heat flux at brick perimeter
Re	flow hole local Reynolds number
R_i	radiosity of surface i
s	flow hole spacing
T_c	ceramic temperature at flow hole surface
T_g	flow hole gas temperature
T_{gb}	blowdown gas temperature
T_i	temperature of surface i
T_1	brick perimeter ceramic temperature
T_2	containment tube temperature
Z	distance from flow hole entrance
α	ceramic thermal expansion coefficient
β	volume coefficient of expansion of an ideal gas
σ	Stephan-Boltzmann constant
σ_{max}	maximum tantential stress at the flow hole surface
μ	perimeter gap gas viscosity

Symbol	Description
ε_i	emissivity of surface i
ρ	reflectivity of surface i
ν	ceramic Poisson's ratio

ABSTRACT

Thermal stresses were calculated for an experimental magnetohydrodynamic cored ceramic brick regenerative air preheater. The finite element method was employed for determining both temperature and stress distributions for individual ceramic core bricks at typical cyclic equilibrium operating conditions. Maximum stress values and their locations in the hexagonal core bricks were calculated and compared with values predicted by an earlier, more approximate method as well as with failure modes in an actual preheater. The maximum stresses were found to be circumferential; that is, acting perpendicularly to the direction of the gas flow passages.

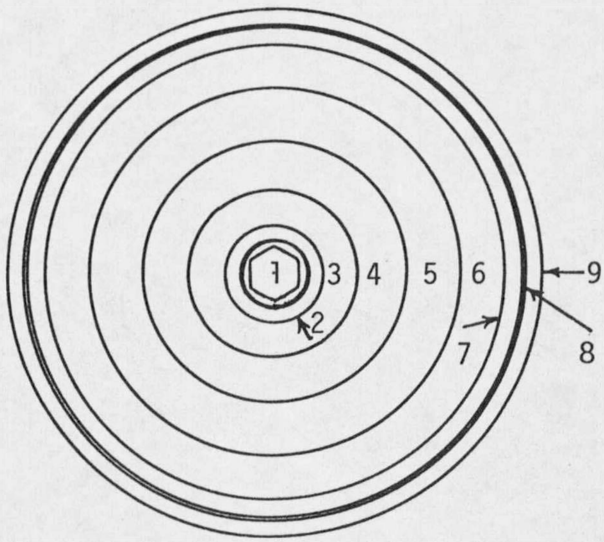
CHAPTER I

INTRODUCTION

In the open-cycle magnetohydrodynamic (MHD) system, there is a requirement for combustion intake air at temperatures on the order of 1800°K. One method proposed for accomplishing this involves use of a cored ceramic brick regenerative heat exchanger, or preheater. The operational modes of the preheater are the alternating reheat and blow-down cycles, wherein the preheater core is heated by combustion exhaust gases and cooled by combustion intake air, respectively.

Coal is the fuel proposed for MHD systems under study at Montana State University. The use of coal as fuel results in liquid coal slag being present in the combustion exhaust gases. This causes complications in the operation of the air preheaters due to slag deposition and run-off on the gas flow passage walls and slag saturation of the ceramic core material. An experimental air preheater, the Moderate Temperature Slag Flow Facility (MTSFF) has been constructed at Montana State University to study these problems.

The MTSFF consists of a columnar core of hexagonal ceramic bricks. Surrounding the core is a circular ceramic containment tube, several layers of ceramic insulation, a steel pressure vessel, and a final layer of fiberglass insulation. There is a small air space between the circular containment tube and the hexagonal core. The core bricks are symmetrically drilled with nineteen holes, 19.1 mm. in diameter (see Figures 1a and 1b).



1 - ceramic core
2 - containment tube
3-6 - ceramic insulation
7 - cerafelt blanket
8 - steel shell
9 - fiberglass insulation

Figure 1a MTSFF cross section

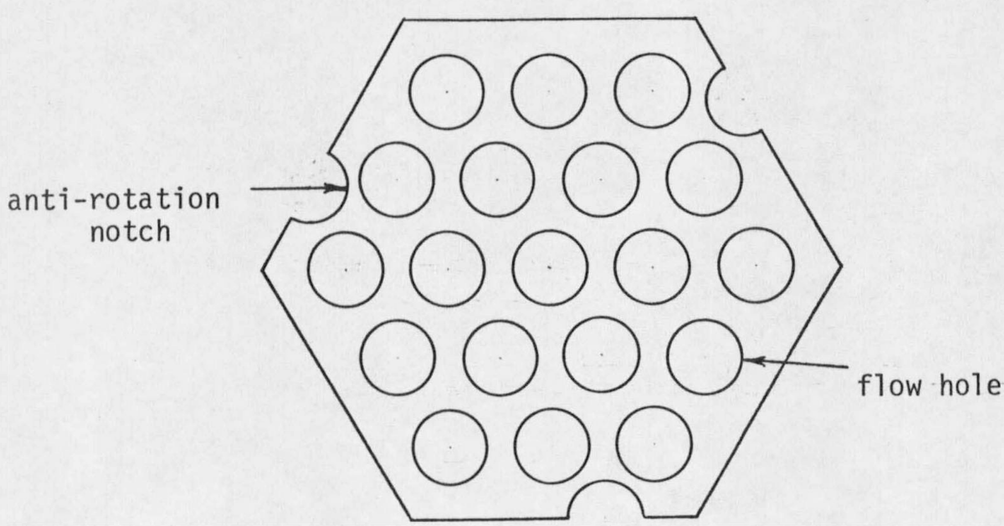


Figure 1b Hexagonal core brick cross section

The primary purpose of this thesis is to investigate thermal stresses in the ceramic core bricks of the MTSFF due to alternate heating and cooling in the reheat and blowdown cycles. Also of interest is the comparison of these predicted stress levels with those predicted by an earlier technique, and the extension of the analysis to a full scale, operational air preheater.

CHAPTER II

LITERATURE REVIEW

Traditionally, analytical methods for evaluation of thermal stress have been limited to simple geometries, for which an analytical solution of the heat conduction equation exists. Upshaw [1], in a MHD air preheater design study used this method by approximating the complex 19-hole cored brick pattern as a bundle of cylindrical tubes. Using this model, he then obtained a quasi-steady-state temperature distribution for heating or cooling of the tubes from their inner surface. Then, by considering the tubes to be of infinite length, he was able to use thermal stress relations presented by Timoshenko and Goodier [2] for free standing infinite cylinders.

An alternative to this problem simplification is the use of numerical methods. Huebner [3] lists the two principal numerical methods for heat transfer and stress analysis as the general finite difference and finite element methods. Both are suitable for solving the corresponding governing equation over a field of interest, but he also points out that the finite difference method becomes increasingly difficult to use for complex geometries or unusual boundary conditions. Huebner [3] and Gallagher [4] both state that the primary advantage of the finite element method is the treatment of complex geometries and boundary conditions. This, in addition to the extensive availability of general purpose finite element computer codes for both heat transfer [5, 6, 7, 8] and stress analysis [8, 9] makes the finite element method an attractive one to use for this problem.

Boundary condition data for heat transfer and stress analysis of the preheater core bricks is readily available. Recent work has been done by Herrick [10] on the thermal simulation of the MTSFF, and experimental data on heat transfer and temperature profiles is also available from operation of the facility.

CHAPTER III

THEORY

Temperature and Stress Fields

Upshaw [1] describes the preheater temperature distribution and, consequently, the thermal stress distribution as consisting of three types. These are the axial and radial temperature distributions extending over the entire preheater body and the localized radial temperature distributions between flow holes. The axial temperature profile is relatively well defined. Figure 2 shows a typical MTSFF axial temperature profile taken from thermocouple data during facility operation. All the data falls within five percent of a linear curve fit. This is significant because a linear temperature distribution of this type will produce no stress in the preheater core [11]. Herrick [10] shows that the axial heat flux at any one point in the preheater core is less than 0.01 percent of the radial heat flux, an insignificant amount. Thus, axial effects can be ignored for both stress and heat transfer calculations.

The remaining two preheater temperature distributions, radial body and localized 'radial', need not be considered separately. They both fall in the same plane, perpendicular to the preheater core axis. Proper selection of core brick boundary conditions will yield a complete combined solution through the finite element analyses.