Design of a high temperature falling bed air preheater for direct coal-fired MHD power generation using liquid slag droplets

by Raymond Lee Prill

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

Abstract:
A unique design for a falling liquid droplet heat exchanger is presented. The major problem associated with this type of heat exchanger, that of obtaining uniformly sized liquid droplets, has been solved by utilizing vibration induced atomization of the liquid. With this method the drops are formed by disturbing a liquid capillary jet by either vibrating a distributor plate through which the liquid flows or by holding the plate stationary and producing the disturbance with external sound pressure waves. Specific use of this type of heat exchanger as a direct coal fired air preheater for MHD power generation is examined. Digital solution of the governing equations has determined the effect of particle size and size distribution on the chamber size requirement. Comparisons with other MHD preheater design concepts, including the cored brick, show the present design has numerous advantages.

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Signature Raymond L Pill

Date May 18, 1977

DESIGN OF A HIGH TEMPERATURE FALLING BED AIR PREHEATER FOR DIRECT COAL-FIRED MHD POWER GENERATION USING LIQUID SLAG DROPLETS

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont)

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

SYMBOL	DESCRIPTION
a	acceleration of gravity
a_r	Rosseland absorption coefficient
c	specific heat
d	droplet diameter
f	shadowing factor or frequency function
h	heat transfer coefficient
i_b	black body radiative intensity
k	thermal conductivity
ℓ	length
$\dot{m}$	mass flow rate
n	droplet number density
q	heat flux (per unit area and time)
r	radius
s_d	standard deviation
t	time
x	distance from the top of the chamber
A	area
C_D	drag coefficient
D	diameter
F	frequency
Gr	Grashof number

SYMBOL	DESCRIPTION
H	overall heat transfer coefficient
L	chamber length
N	total number of descrete sizes of droplets
Nu	Nusselt number
P	chamber pressure
Pr	Prandtl number
Qr	radiative heat transfer rate
Qcov	convective heat transfer rate
R	gas constant or radius
Re	Reynolds number
T	temperature
T_1	temperature at top of upper chamber
T_2	temperature at bottom of upper chamber
T_3	temperature at top of lower chamber
T_4	temperature at bottom of lower chamber
U	dimensionless velocity parameter
V	velocity
V_1	velocity at top of upper chamber
V_2	velocity at bottom of upper chamber
V_3	velocity at top of lower chamber
V_4	velocity at bottom of lower chamber

SYMBOL	DESCRIPTION
α	absorption coefficient
β	volume coefficient of expansion
η	dimensionless distance
ϕ	dimensionless temperature parameter
μ	dynamic viscosity
ρ	density
σ	Stefan-Boltzmann constant
σ_s	surface tension
Ω	solid angle
ψ	dimensionless quantity characterizing heat transfer chamber requirements

SUBSCRIPTS

a	air
c	capillary
g	gas
in	inner
j	jet
m	mean
max	maximum
min	minimum
o	outer

SYMBOL	DESCRIPTION
opt	optimum
r	relative or radiative
s	slag
term	terminal
w	wall

SUPERSCRIPTS

'	derivative
*	dimensionless quantity

ABSTRACT

A unique design for a falling liquid droplet heat exchanger is presented. The major problem associated with this type of heat exchanger, that of obtaining uniformly sized liquid droplets, has been solved by utilizing vibration induced atomization of the liquid. With this method the drops are formed by disturbing a liquid capillary jet by either vibrating a distributor plate through which the liquid flows or by holding the plate stationary and producing the disturbance with external sound pressure waves. Specific use of this type of heat exchanger as a direct coal fired air preheater for MHD power generation is examined. Digital solution of the governing equations has determined the effect of particle size and size distribution on the chamber size requirement. Comparisons with other MHD preheater design concepts, including the cored brick, show the present design has numerous advantages.

CHAPTER I

INTRODUCTION

The efficiency of a fossil fueled open cycle magnetohydrodynamic power generating plant depends strongly on the temperature of the working gas. The required combustion temperatures, on the order of 3000K, can be achieved by either preheating the combustion air to a high temperature, around 2000K, or by use of oxygen enriched air. Because of the amount of oxygen that would be needed in a large scale MHD power plant, the latter of these methods was not considered in this study.

There are two basic types of air preheaters for open cycle MHD applications - the directly fired and indirectly fired. The directly fired preheater utilizes the thermal energy of the exhaust gas from the MHD channel to preheat the air while the indirectly fired facility uses the exhaust gas from a separately fired, clean fuel combuster. The indirectly fired preheater, though not having to withstand the deleterious properties of the fly ash slag, sulfur, and potassium seed contained in an MHD exhaust gas, would require an expensive clean burning fuel such as natural gas and would lower the overall plant efficiency. Therefore, the full exploitation of the efficiency advantages of an MHD power plant is dependent on the employment of high temperature directly fired air preheaters.

Four types of preheater designs have in the past been considered for coal fired MHD applications:

1) the chequerwork packed bed preheater
2) the packed pebble bed preheater
3) the cored brick packed bed preheater
4) the falling bed preheater

All of these are regenerative type heat exchangers.

Polish researchers have sized the chequerwork type preheater and found the dimensions quite large (1). Creep of the ceramic bricks at the bottom of such a massive chequerwork is a serious problem. The packed pebble bed type preheaters have the inherent problem of plugging up from the coal slag deposits, though they are feasible in an indirectly fired facility (2). The cored brick preheater offers both the possibility of not plugging from the exhaust gas coal slag deposits and good thermal effectiveness (3).

All packed bed type preheaters (chequerwork, pebble bed and cored brick) operate in a cyclic mode of heat-up and blow-down. This requires large gas valves in the MHD exhaust gas flow stream operating periodically and sealing against the differential pressure between the inlet and outlet of the MHD channel (approximately 7 atmospheres) at high temperatures (around 2000K). These valves represent large capital costs and raise serious reliability questions. This problem, teamed with the problems of finding a durable bed material and reducing plugging and fouling to an acceptable level, has caused preheater design to lag behind development of other MHD components.

The falling bed concept represents one solution to the problems of other directly fired MHD preheater design concepts. This design employs heat transfer from particles falling through a counterflow of gas. In the MHD application the particles would be heated in one set of chambers by the exhaust from the MHD channel. These heated particles would then fall through a counterflow of combustion air in a second chamber. Figure 1.1 shows the flow process involved. Continuous recycling of the bed materials eliminates any valves in the exhaust gas flow. The large surface-area-to-mass ratio of the particles in the falling bed preheater give it potential for high heat transfer rates.

Two types of bed material for the falling particle preheater have been proposed; solid particles of a material like alumina (4, 5) and liquid droplets of a material like coal slag. Extensive research was done on the atomization of liquid slag by a team of English engineers (6). These studies were focused on the use of twin jet atomizers, breaking up a jet of liquid slag with a jet of air. This type of atomizer had the disadvantage of a wide dispersion of droplet sizes, causing large chamber length requirements.

If the droplets are mono-disperse in size, they can be partially "floated" by the gas and the chambers can be very compact. As the droplet size dispersion increases the velocity of the gas must be decreased to avoid elutration of the smaller particles and the chamber length must be increased to provide adequate residence time for heat

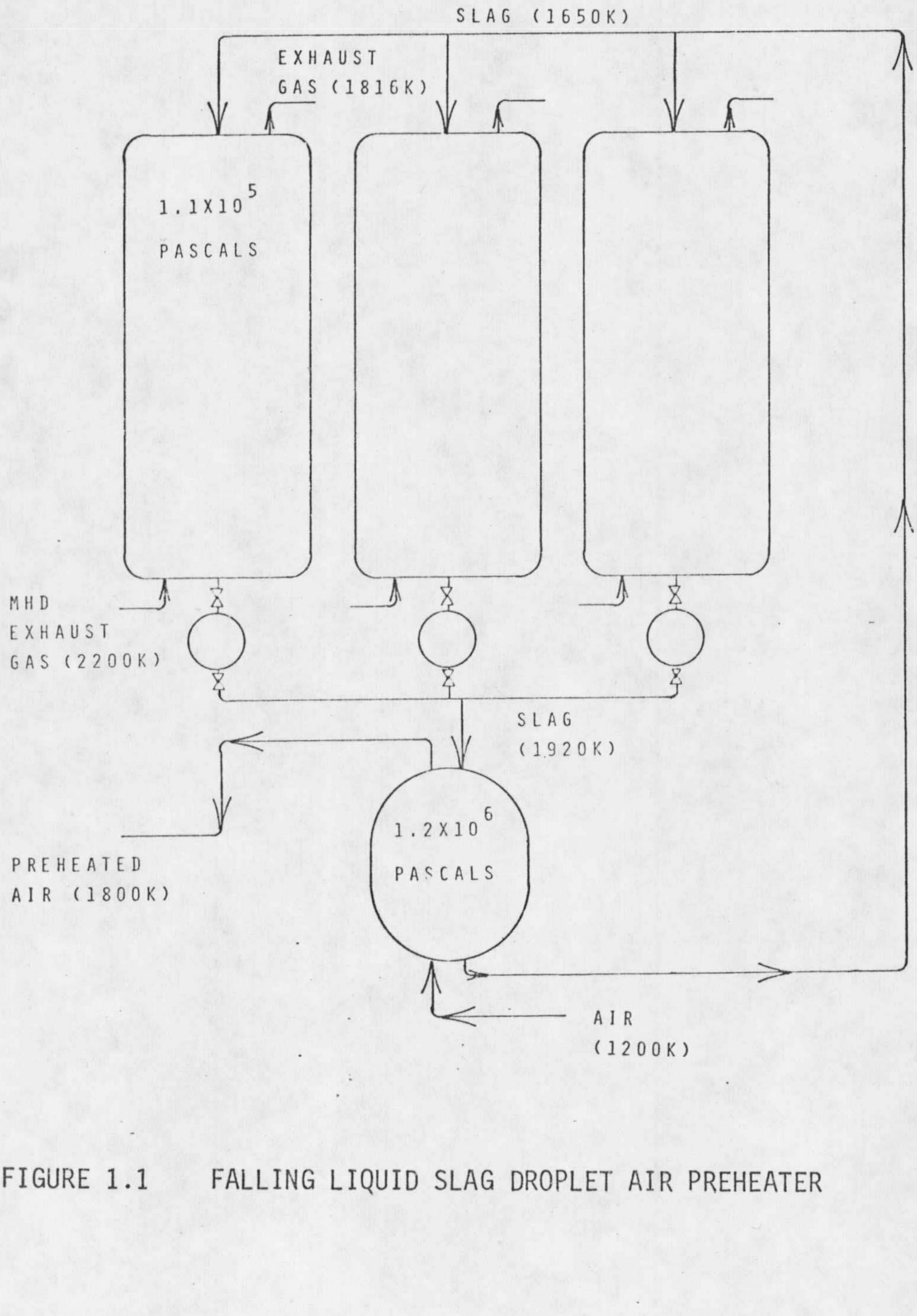

FIGURE 1.1 FALLING LIQUID SLAG DROPLET AIR PREHEATER

transfer to or from the larger droplets. Therefore, the feasibility of a falling bed heat exchanger using liquid slag as the bed material is dependent on a narrow dispersion of the droplet diameters.

Mono-disperse sprays have been achieved by vibration induced atomization. With this method the droplets are formed by disturbing a liquid capillary jet by either vibration (7, 8) or with external sound pressure waves (9, 10). Experimental data has shown that drops uniform in diameter to within five percent of the mean can be obtained using liquids as inviscid as water and as viscous as glycerin.

The concept of the above described droplet generator and the falling bed heat exchanger using liquid slag as the heat transfer media are combined in the following preheater design. It is shown that narrow droplet size distributions obtainable with the droplet generator can render an efficient and compact directly fired, high temperature preheater for open cycle fossil fueled MHD applications. Some of the off design operational characteristics are also considered.

CHAPTER II

ANALYTICAL MODEL

The differential equations for the heat transfer within the heat exchanger were obtained from basic principles.

Radiative Transfer

Radiative energy exchange between any two droplets in the chamber depends upon the solid angle subtended by one droplet as viewed from the other. Therefore, it is necessary to derive an expression for the shadowing effect of the particles.

Consider an incremental sphere of radius ℓ and thickness $d\ell$ centered about a droplet of diameter d_i as shown in Figure 2.1. Assume the sphere is occupied by droplets of diameter d_m located randomly with an average number density n. Let $\Omega(\ell)$ represent the total solid angle subtended by all of the droplets within the sphere. The fraction of solid angle not yet shadowed by these droplets is

$$f(\ell) = (4\pi - \Omega(\ell))/4\pi \qquad 2.01$$

Then the solid angle subtended by the droplets within the incremental sphere is

$$d\Omega(\ell) = \left(\frac{n\pi d_m^2}{4\ell^2}\right) (4\pi\ell^2 d\ell)\ f(\ell) \qquad 2.02$$

This yields the differential equation

$$\frac{d\Omega}{d\ell} + \frac{n\pi d_m^2}{4}\ \Omega(\ell) - \pi^2 d_m^2 n = 0 \qquad 2.03$$

With the boundary condition

$$\Omega(o) = 0 ,$$

the solution is

$$\Omega(\ell) = 4\pi(1-e^{-n\pi d_m^2 \ell/4}) \qquad 2.04$$

Therefore,

$$f(\ell) = e^{-n\pi d_m^2 \ell/4} \qquad 2.05$$

To derive the equations for the net radiation it was assumed that the droplets are black bodies. It was further assumed that the droplets form an optically dense cloud and the radiation penetration distance is small compared with the distance over which significant temperature changes occur. Thus the gas was considered transparent. After the equations were solved, this latter assumption was checked and the absorption by the gases was found to be small (11). The radiative transfer from a droplet of diameter d_m in the annulus to the droplet of diameter d_i as shown in Figure 2.2 is

$$Qr_{2\to1} = \frac{i_b \pi^2 d_i^2 d_m^2}{16\ell^2} \; f(\ell) \qquad 2.06$$

where

$$i_b = \sigma T_{sm}^4/\pi \qquad 2.07$$

and

$$\ell^2 = x^2 + r^2 \qquad 2.08$$

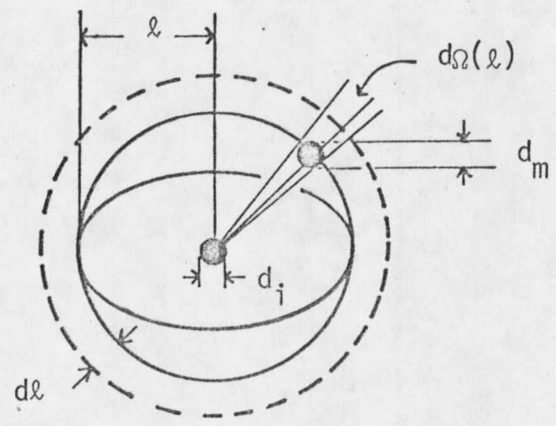

FIGURE 2.1 INCREMENTAL SPHERE FOR DERIVATION OF SHADOWING EFFECT

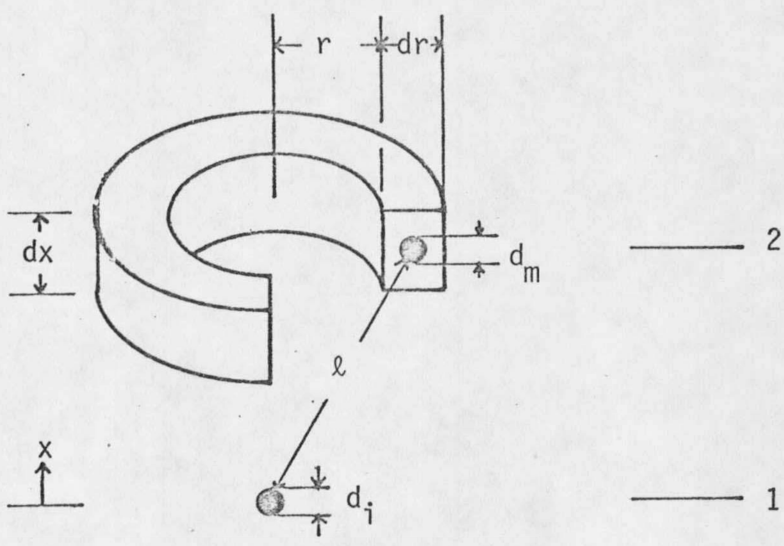

FIGURE 2.2 INCREMENTAL ANNULUS FOR DERIVATION OF RADIATIVE TRANSFER