Design of an indirect-fired falling-particle air preheater for MHD power generation
by Chris Dewey Jensen

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

Abstract:
A preliminary design for an indirect-fired falling-particle air preheater for a 400 MW (thermal) MHD power generation plant was made.

The project was broken down into three major parts: material properties prediction, development of a theoretical model, and capital and annual cost estimation of the overall design.

A theoretical model was developed for an indirect-fired cored-brick air preheater. Capital and annual costs were estimated and compared to those of the falling-particle air preheater. It was found that overall air preheat systems involving these two designs would have approximately the same capital costs of ~ \$44 x 10^6, and annual costs of ~\$6 x 10^6.

An economic comparison was then made between overall indirect-fired air preheat designs, and overall direct-fired designs. In both the falling-particle and cored-brick cases, the capital cost of the indirect-fired design was approximately 50% greater than the capital cost of the direct-fired design.

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Signature Chris Dewey Jensen

Date June 21, 1976

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont).

TABLE OF CONTENTS(Cont).

TABLE OF CONTENTS (Cont).

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

(Excludes terminology used exclusively in computer program. See Appendix C-7 for definitions of program variables).

SYMBOL	EXPLANATION	UNITS
A	particle surface area	ft^2
A_c	particle cross-sectional area	ft^2
C_D	drag coefficient	dimensionless
C_p	specific heat (constant pressure)	BTU/lb_m°F
D_c	inside column diameter	ft
F_d	drag force	lb_f
N_T	total number of holes in cored-brick column	
Nu	Nusselt number, hD/k	dimensionless
Pr	Prandtl number, $C_p\mu/k$	dimensionless
R	heat transfer resistance	°F hr/BTU
Re	Reynolds number, $Du_b\rho/\mu$	dimensionless
St	Stanton number, Nu/RePr	dimensionless
T_w	outside wall temperature	°R
T_s	particle temperature	°R
T_g	gas temperature	°R
T_∞	ambient temperature	°R
U_o	overall heat transfer coefficient	BTU/hrft^2°F
d_o	hole diameter in cored-brick	ft

NOMENCLATURE (Cont)

SYMBOL	EXPLANATION	UNITS
d_p	particle diameter	ft
f	friction factor	dimensionless
g	acceleration of gravity	ft/sec^2
g_c	gravitational constant, 32.17	$ftlb_m/lb_f sec^2$
h	convective heat transfer coefficient	$BTU/hrft^2 °F$
k	thermal conductivity	BTU/hrft°F
q	heat transfer rate	BTU/hr
U_A	gas velocity	ft/sec
U_T	particle terminal velocity	ft/sec
V	particle velocity	ft/sec
W_g	gas mass flow rate	lb_m/hr
W_s	particle mass flow rate	lb_m/hr
X	vertical distance from top of column	ft
δ	insulation thickness	ft
μ	viscosity	$lb_m/ftsec$
ρ_g	gas density	lb_m/ft^3
ρ_s	particle density	lb_m/ft^3
θ	time	sec
τ_w	shear stress at wall	lb_f/ft^2
ΔX	incremental change in X	ft
ΔP	pressure drop	lb_F/in^2

ABSTRACT

A preliminary design for an indirect-fired falling-particle air preheater for a 400 MW (thermal) MHD power generation plant was made. The project was broken down into three major parts: material properties prediction, development of a theoretical model, and capital and annual cost estimation of the overall design.

A theoretical model was developed for an indirect-fired cored-brick air preheater. Capital and annual costs were estimated and compared to those of the falling-particle air preheater. It was found that overall air preheat systems involving these two designs would have approximately the same capital costs of $\sim$ \$44 x 10^6, and annual costs of $\sim$\$6 x 10^6.

An economic comparison was then made between overall indirect-fired air preheat designs, and overall direct-fired designs. In both the falling-particle and cored-brick cases, the capital cost of the indirect-fired design was approximately 50% greater than the capital cost of the direct-fired design.

INTRODUCTION

CONVENTIONAL TURBINE AND MHD POWER GENERATION

Magnetohydrodynamic (MHD) power conversion is a method of generating electricity with features similar to those of a conventional steam tubrine driven generator. These similarities will be discussed, and then features peculiar to MHD power conversion will be discussed.

Figure 1 illustrates a very simplified steam turbine driven generator and a MHD generator. In the case of the steam turbine generator, the thermal energy of hot combustion products (formed by the burning of some fossil fuel) is transformed into latent energy by vaporizing water to steam. The transformation to mechanical energy is accomplished by expanding the steam against turbine blades. Finally, the turbine shaft rotates a conductor (the armature) in a stationary magnetic field (the stator). As the lines of magnetic flux are broken, a net electromotive force and resulting current flow is created in accordance with Faraday's laws of induction. It should be pointed out that the working gas in the turbine could be any hot, high pressure gas, as well as steam.

The MHD power conversion system has a number of similarities to the turbine generator. In the MHD case, the conductor which breaks the lines of magnetic force of the stationary magnetic field is a hot, electrically conducting fluid, usually a gas. Thus the thermal energy of the conducting fluid is transformed directly to electrical energy. The system consists of an expanding duct through which the hot gas flows, which is lined on two opposite sides with electrodes. The electrodes

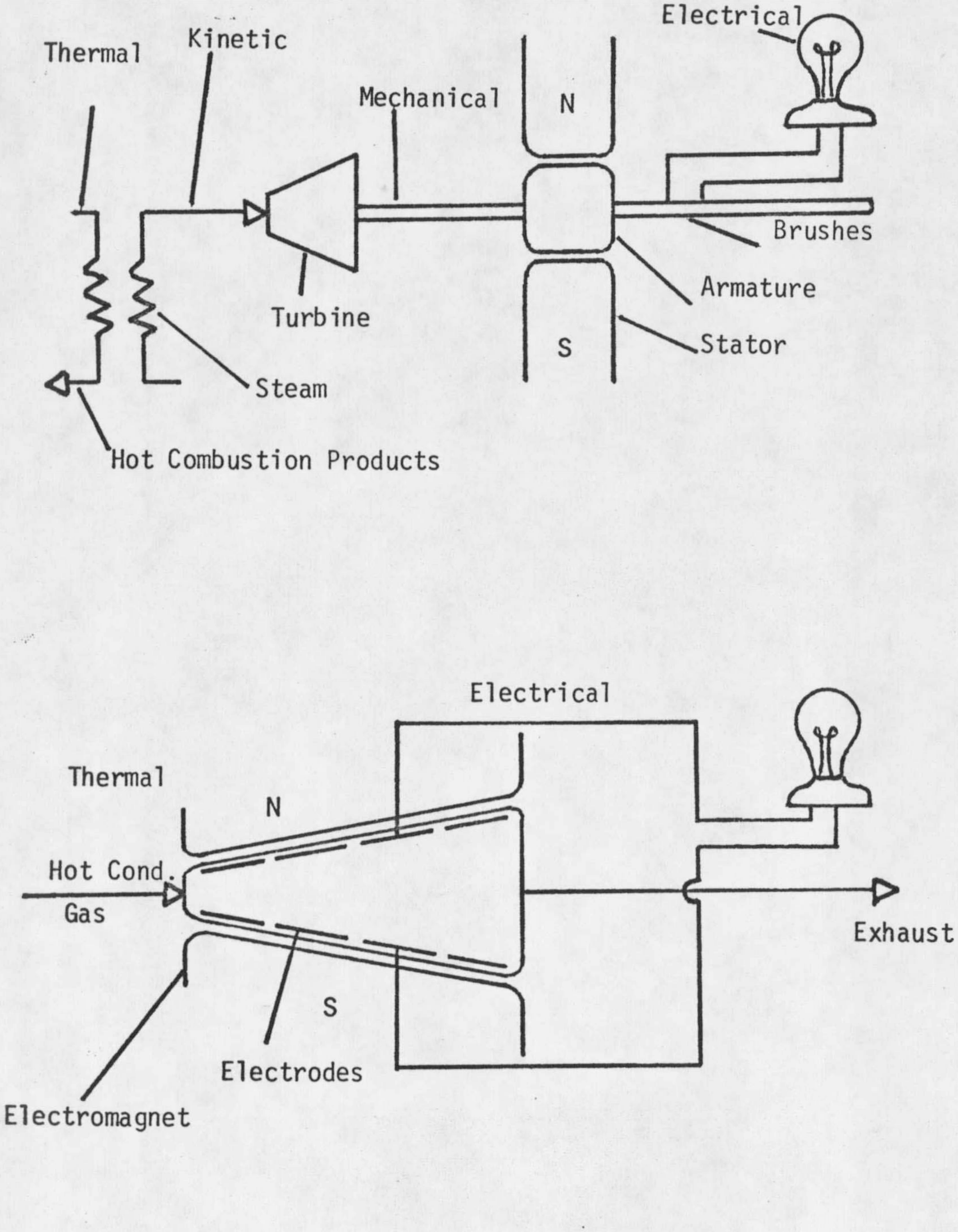

FIGURE 1. CONVENTIONAL TURBINE AND MHD POWER GENERATION SYSTEMS COMPARISONS

carry the current to the external load circuit in the same fashion as the brushes in the conventional generator.

It should be noted here that the rotational motion of the armature in a conventional generator creates a alternating current, whereas the continuous motion of the gas past the electrodes in an MHD generator creates direct current.

The two types of MHD systems possible are open cycle and closed cycle. In the closed cycle case, the conducting fluid is recycled and regenerated through the use of heat exchangers. Examples of this type of system are cycles involving noble gases, and liquid metals. In the open cycle case, the conducting fluid passes through the MHD duct only once. Since this paper is directed toward the design of heat exchange components for open cycled fossil-fueled MHD systems the closed cycle system will not be discussed further.

In an open cycle MHD system, the hot gas (combustion products of some fossil fuel) is made an electrical conductor by the addition of a seed, such as K_2O or K_2CO_3. The low ionization potential of the seed enables a free flow of electrons within the gas. A conducting gas of this type is called a plasma. The electrical conductivity of the gas is a relative measure of the ease in which the gas will conduct electricity. The optimum seed concentration is about 1-5% by weight (1,2).

COMPARISON OF EFFICIENCIES

In the type of power conversion systems discussed so far, thermodynamic efficiency is optimized by maximizing the temperature of the working gas. The presence of highly stressed moving parts in a turbine generator becomes the limiting factor in the working gas temperature, and thus in the generator efficiency. As a result of this, the electrical efficiencies obtained in conventional steam turbine power plants is between 30-45%. In the case of MHD systems, no moving or highly stressed parts are present, and all parts are readily accessible to external cooling. Thus the limiting factor in MHD efficiency is the temperature of the working gas itself, which can be much higher than the maximum temperature in a turbine. It is foreseen that working gas temperatures as high as 5000-6000°F are possible for MHD applications. Efficiencies of systems employing present technology are predicted to be about 50%. Advanced systems are foreseen to have efficiencies as high as 60%. As a further comparison the average efficiency of a nuclear fission power generating facility is 32%. Thus an advanced MHD plant would have 1.5 times the efficiency of a conventional steam turbine plant, and 1.9 times the efficiency of a conventional nuclear plant. It should be noted here that the advantage of an MHD system is not is high efficiency alone, but its ability to convert thermal to electrical energy in much higher temperature ranges than turbine generators. As a result, the exhaust gases from the MHD duct would be transferred to a conventional gas or steam turbine generating facility, or "bottoming" plant. The total power output of the facility would be about evenly divided between the MHD plant and the bottoming plant (1,3).

THE NEED FOR PREHEATED AIR

The working gas temperatures necessary for efficient MHD power generation are well above gas temperatures accessible by conventional combustion methods. The combustion of coal with ambient air gives a maximum temperature of about 3000°F. However, efficient MHD power generation requires a temperature of about 5000°F. Two methods are available in achieving this temperature. The first is the use of excess oxygen. In view of the high cost of a facility capable of producing the amounts of oxygen which would be necessary for a commercial scale MHD installation, this method is looked upon as uneconomical with present technology. The second method involves preheating the combustion air before it is used to burn the coal. This method has been used extensively in the steel industry. Conventional tube and shell heat exchangers can be used to preheat air to about 1700°F. To reach the temperature necessary for MHD power generation, an air preheat temperature of about 3100°F is required. Thus a heat exchange system is needed which will raise the temperature of air from 1700°F to 3100°F. A number of systems are presently being looked at.

DIRECT AND INDIRECT-FIRED AIR PREHEATERS

Air preheaters are of two basic types according to how they fit into the overall MHD process - direct-fired and indirect-fired, as shown in Figure 2. The direct-fired air preheater utilizes the thermal energy of the MHD exhaust gas, which leaves the MHD duct at about 3300°F, to directly preheat air. The indirect-fired air preheater utilizes the thermal energy of exhaust from a separately fired clean fuel combustor to preheat the combustion air. The direct-fired design has three basic disadvantages. First, the MHD exhaust is laden with vaporized seed and slag, both of which are highly corrosive. Second, as the exhaust gas transfers heat in the air preheater, both the seed and slag condense, coating the internal works of the preheater. This solid residue would have to be continuously removed, not only from an operations standpoint, but also because the cost of the seed makes recycle imperative. Third, the inlet pressure to the MHD duct must be $\sim$8 atm in order that the gas can push itself through the duct. As a result of this, the preheated combustion air must be pressurized to 8 atm. However, the outlet pressure from the MHD duct is $\sim 1\frac{1}{2}$ atm. Thus, there will be a pressure differential of $\sim 6\frac{1}{2}$ atm. between the exhaust gas side and the air side of the preheater. The indirect-fired air preheater has none of these disadvantages. Since the fuel is clean, no problems with seed and slag are encountered. Also, since the inlet pressure of the combustion products of the fuel can be arbitrarily set, the hot gas side and the