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HEAT-EXCHANGER NEEDS FOR RECOVERING WASTE HEAT IN THE GLASS-MAKING INDUSTRY

Final Report

February 1983

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Prepared for the
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Executive Summary of the Final Report on
Heat-Exchanger Needs for Recovering Waste Heat
in the Glass-Making Industry

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Prepared for

Department of Energy
Energy Conservation Branch
Dr. W. H. Thielbahr, Chief
Contract No. DE-FG07-81ID12225

June 1982

PREFACE

The content of this report is directed at individuals who have an interest in recovering heat energy from high-temperature, dirty, corrosive waste-heat streams. This report contains an assessment of the state-of-the-art of waste-heat-recovery technology in the glass-making industry. The sponsor of this assessment is the U. S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Energy Systems Research. The work reported herein was performed under Contract DE-FG07-81ID-12225 and is a part of the Heat Exchanger Technology project of the Energy Conversion and Utilization Technology (ECUT) Program.

Both papers, which comprise this report, were presented at the International Conference On Fouling of Heat Exchanger Surfaces, White Haven, Pennsylvania, October 31 - November 5, 1982.

PROJECT OBJECTIVE

To justify possibilities for and problems associated with heat recovery in the glass-making industry. To recommend heat-exchanger research that will support heat recovery beyond that used in present installations.

INTRODUCTION

The Stone, Clay, Glass industry (SIC 32) is one of the six largest energy consuming industries. This industry uses vast amounts of oil, gas and electricity. The dominant energy consumption is for the melting process. Due to the high melting temperature, exhaust gases leave the melting furnace at approximately 2800°F. Most glass plants use brick "checkers" periodic flow regenerators to extract heat from the furnace exhaust gases, which preheats the combustion air. The exhaust gas leaves the checkers regenerator at 1000-1200°F. These 1200°F gases are presently exhausted to the atmosphere.

The primary focus of this project is to identify possibilities for secondary heat recovery by removing additional heat from the 1200°F "waste" gases.

This project was supported by the U.S. Department of Energy, Energy Conservation Branch. Dr. W. H. Thielbahr was the DOE Program Manager. The project work was performed over the period August 1, 1981 through July 30, 1982.

METHOD OF APPROACH

The project objectives were met by a detailed survey of glass making technology, performed via literature and field surveys. The major tasks included:

1. Understanding the technology of the glass making process, and identifying the types and amounts of energy employed, and the temperature and composition of the hot gases.
2. Identify possible uses for recovered heat.
3. Establish the types of heat exchange equipment needed for heat recovery, and transfer of this energy to a needed use.
4. Define the fouling and corrosion potential of the exhaust gases as a function of gas temperature and candidate heat exchanger type.
5. Propose innovative heat exchange types or process modifications that reduce the fouling and corrosion potential.
6. Establish R&D needs that will support the use of additional heat recovery by the glass industry.

An extensive literature search was conducted to identify the state-of-the-art. Numerous contacts were made with glass manufacturers, heat exchanger manufacturers, cogeneration system designers, and other related experts. This was achieved by plant visits, letters and telephone communications.

The personnel associated with this project were:

Dr. R. L. Webb, Project Director
Dr. A. K. Kulkarni, Principal Investigator
Mr. D. Marchiori, Graduate Assistant
Mr. R. Durbin, Graduate Assistant
Mr. Y. J. Wang, Graduate Assistant

The project was divided into three technical areas. These are:

1. Glass manufacture technology, heat recovery options and system design.
2. Exhaust gas fouling and corrosion.
3. Heat exchange technology.

TECHNICAL SUMMARY

A summary of the program results is given in the three attachments. The first two are technical papers presented at the International Fouling Conference held in White Haven, Pennsylvania, October 31 - November 5, 1982, which was sponsored by the Engineering Foundation. The technical summary is described in:

1. Fouling and Corrosion in Glass Furnace Exhausts, by A. K. Kulkarni, Y-J. Wang and R. L. Webb.
2. Heat Exchangers for Secondary Heat Recovery from Glass Plants, by R. L. Webb, D. Marchiori, R. E. Durbin, Y-J. Wang and A. K. Kulkarni.
3. Research and Development Needs Statement, by R. L. Webb and A. K. Kulkarni. This document describes three R&D projects that will advance the use of secondary heat recovery in the glass industry.

FOULING AND CORROSION IN GLASS FURNACE REGENERATORS

A. K. Kulkarni*, Y-J. Wang**, and R. L. Webb*

ABSTRACT

Fouling and corrosion problems in the regenerative glass furnaces are reviewed in this paper. First, the composition of glass furnace gases and carryover is presented. Fouling and corrosion mechanisms, which are different in the top zone (1400 C - 1000 C) and bottom zone (1000 C - 600 C) of regenerator, are then examined separately. Finally current and suggested methods of minimizing fouling and corrosion in regenerators are discussed. Fouling and corrosion by exhaust downstream of regenerators and possibilities of heat recovery using heat exchangers will be presented separately.

INTRODUCTION

The Stone, Clay, and Glass Industry is one of the six largest energy consuming industries. The dominant energy consumption process in glass making industry is the melting process in furnace. Exhaust gases from a glass furnace, typically at 1400 to 1600 C, are cooled down to about 475 to 650 C in brick regenerators before they are rejected to the atmosphere. These high temperature gases are extremely corrosive and have a tremendous fouling potential, which makes the heat recovery a challenging task. There are three zones from the fouling and corrosion point of view: (i) top part of the regenerator, (ii) bottom part of the regenerator, and (iii) downstream of the regenerator. This paper presents results of fouling and corrosion in the top and bottom parts of the regenerator. A later paper by Webb et. al¹, will concentrate on the possibilities for secondary heat recovery from exhausts downstream of the regenerator and associated fouling and corrosion problems. This study is part of a program sponsored by the Department of Energy which included a literature survey, visits to several glass manufacturing plants, and discussions with experts in the glass industry. In the following paper, first characterization of the glass furnace exhaust is presented, followed by the discussion of fouling and corrosion problems in regenerators, and finally methods of minimizing fouling and corrosion are briefly reviewed.

CHARACTERIZATION OF GLASS FURNACE EXHAUST

The temperature and composition of a glass furnace exhaust in general depend mainly upon the glass type, fuel type, type of furnace, and the furnace operating temperature. As the furnace exhaust is

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cooled down in the regenerator, from approximately 1450 C at the entrance to 600 C at the exit of regenerator, the composition changes due to fractional condensation and particulate deposition, and therefore the composition and temperature also depend upon the location in regenerator. Overall, the exhaust consists of (i) combustion products, such as CO_2 , H_2O , CO , NO_x , and SO_x , (ii) excess air and unburned hydrocarbons, and (iii) portions of batch material, such as Na_2O , SiO_2 , CaO , cullet dust, etc.

A recent report by Airesearch Manufacturing Company of California² presented an excellent study on glass furnace exhaust characterization, which is the source for many of the following details. The exhaust is composed of solid particulates, liquids, condensible vapors, and gases. The particulate concentration ranges from 0.011 to 0.693 lbm/hr per ton/day of production with an average of approximately 0.063 lbm/hr per ton/day. Because of relatively low velocity of the gases and long path in the regenerator, most of the particles larger than a few microns drop out. Finally, in the exhaust leaving the regenerator, more than 90 percent particles are less than 2 microns in size and major portion of particulate matter is in submicron particle size range. Table I shows major constituents of the particulate matter at different locations in the furnace.^{2,3,4} It should be noted that most of the Na_2O appears in the form of Na_2SO_4 after reacting with SO_3 . Oil and gas fired furnaces differ mainly in the contents of Na_2SO_4 , SiO_2 and V_2O_5 in their exhausts. Most of the SiO_2 particles drop out in the regenerator, hence their composition is much lower at the end of the regenerator. In general, major constituent of the particulates is Na_2SO_4 .

Liquid content in the exhaust is usually difficult to determine and it is also strongly temperature dependent. The most important liquid from fouling and corrosion point of view is molten Na_2SO_4 (melting point 884 C) in the top of regenerator. In vapor form, SO_3 , HCl and HF are important because of their corrosive nature. Results from typical gas analyses upstream of reversal valve are given in Table II below.^{4,5}

TABLE II: GAS STREAM COMPOSITION UPSTREAM OF REVERSAL VALVE^{4,5}

Composition	Gas Fired Furnace ppm(wt)	Oil Fired Furnace ppm(wt)
SO_2	10-80	up to 270
SO_3	0-5	5-30
NO_x	400	400
HCl	15	15
HF	1.5	1.5

The above concentrations vary quite widely depending upon the specific conditions. Note that SO_x content in the exhaust of natural gas fired furnace is much lower than that using oil.

Table 1: Particulate Composition in Exhaust of Glass Furnaces

Compound	Percent Composition					
	Top of the Regenerator					
	a ³	b ³	c ³	d ³	e ⁴	f ²
SiO ₂	11.7	3.5	15.7	5.7	1.88	0.2
Al ₂ O ₃	1.5	1.0	1.2	0.4	0.04	--
Na ₂ O*	28.1	35.0	27.9	31.5	38.4	30.3
K ₂ O*	2.0	3.6	2.6	3.4	0.77	7.7
CaO*	9.2	4.3	6.2	3.7	3.33	1.5
SO ₃ *	43.4	47.0	29.9	50.3	47.5	60.6
V ₂ O ₅	0.14	1.4	0.01	1.5	--	--
Cl	2.7	3.2	4.2	0.2	--	--

a Top of regenerator, end fired gas furnace.

b Top of regenerator, end fired oil furnace.

c Top of regenerator, cross fired gas furnace.

d Top of regenerator, cross fired oil furnace.

e Dust sample from electrostatic precipitator.

f Gas sample upstream of stack.

* Primarily found as sulphates in particulates.

-- Negligible amount.

The above discussion was mostly applicable to soda-lime glass furnace exhaust. Other special types of glass furnaces have slightly different exhaust composition; for example, borosilicate glass has more B_2O_3 and lead silicate glass has more Pb_2O_3 in the exhaust. The melting temperature of these different types of glass is different, which is the more influential factor for exhaust gas composition.

FOULING AND CORROSION IN REGENERATORS

Since fouling and corrosion depend on the gas flow composition and temperature, different mechanisms govern fouling and corrosion at various locations in a regenerator. Therefore, materials used for regenerator packing also are selected accordingly. For the top zone, magnesite bricks with relatively low impurities are suitable, whereas for the bottom zone chrome magnesite bricks are preferred.³ Mechanisms of fouling and corrosion of these two zones are discussed below.

Top Zone of Regenerator (1400 C - 1000 C):

- (i) Bricks are eroded by the high temperature flow of gases. Particulate carryover from the furnace (made up of Na_2O , SiO_2 , Al_2O_3 , V_2O_5 , CaO and cullet dust) along with the eroded bricks tends to settle in the packings and partially block the flow.
- (ii) MgO in magnesite bricks reacts with SiO_2 from furnace exhaust to form forsterite (Mg_2SiO_4). This leads to volume expansion and subsequent crumbling of bricks.³
- (iii) Aluminosilicate bricks, used in earlier regenerators, can be attacked by K_2CO_3 and Na_2SO_4 ³. Also, CaO can be converted to $CaSO_4$ by the attack of SO_3 at temperatures as high as 1300C⁶. These reactions make the bricks weak.
- (iv) Vanadium oxide, V_2O_5 , (which comes mainly from fuel oil) and Na_2SO_4 in the flue gas have been found to attack the bonding material of refractories.⁶⁻¹⁰ The conversion of MgO and CaO to sulfates by SO_3 is accelerated by both V_2O_5 and Na_2SO_4 ; and also the silica is fluxed by the vanadium. The reactions leave behind a liquid phase between MgO grains, lower the melting temperature of bricks, and subsequently the bricks begin to crumble. However, somewhat contradictory views are presented by Morsyan¹¹ and Busby¹² who claim that for usual fuels used in glass furnaces, the concentration of V_2O_5 may be too low to have significant corrosive effect.

Bottom Zone of Regenerator (1000 C - 600 C):

- (i) Sodium sulphate (Na_2SO_4) which is formed by combination of Na_2O and SO_x gases is a liquid above 884°C, and some of it is deposited on the bricks. The liquid phase Na_2SO_4 is not corrosive by itself, however, it dissolves SO_3 to form a dilute solution and transmits the SO_3

activity from the gas phase through the molten sulphate to the refractory surface.⁷ MgO in magnesite bricks is continued to be attacked by the SO₃ to form MgSO₄; also, CaO in the silicate bond of magnesite bricks is converted to CaSO₄. These two reactions weaken the bricks.

- (ii) The sulphates MgSO₄ and CaSO₄, formed as mentioned above, dissolve in liquid Na₂SO₄ to form a ternary eutectic around 650°C.⁷ The eutectic drips down the bricks and probably forms white slag after cooling when gas flow is reversed.
- (iii) The Na₂SO₄, not deposited as liquid on bricks, condenses as white fluffy powder in the gas stream below its condensing point of 884°C. These particulates, along with the white slag dripped from higher temperature zone, plug up the passage ways in the regenerator packing in bottom portion. After several passage ways are plugged up, furnace has to be shut down, and these foulant deposits are removed manually.¹³

A mechanism of Na₂SO₄ vapor condensation fouling on a cool surface (such as a cool brick surface on heat exchanger tube) has been proposed by Brown¹⁴ as depicted in Figure 1. Liquid droplets of Na₂SO₄ are formed in the cool boundary layer of a surface, followed by the movement of the condensate to the tube surface. The liquid droplets then solidify and eventually get deposited on the surface. Brown¹⁴ also proposed a mass transfer equation for vapor temperature above 650 C. Raask¹⁵ confirmed that the rate of deposition remains constant for a wall temperature below 800 C (dew point), and it decreases above 800 C. At 870°C and above the rate of deposition of Na₂SO₄ was almost zero. In other experiments (on exhausts from the combustion of pulverized coal) Samms and Bishop¹⁶ showed that the rate of deposition of sodium and potassium sulfate particles increases with increasing flue gas velocity. This may also be true for glass furnace exhausts.

- (iv) There is also a possibility of formation of alkali iron trisulphates by the reaction of Na₂SO₄, K₂SO₄ and Fe₂O₃ deposits¹⁷, and sodium vanadates by the reaction of Na₂SO₄ and V₂O₅ that are present in the exhaust.¹⁸ These compounds, i.e. sodium trisulphates and vanadates, are corrosive.

METHODS TO MINIMIZE FOULING AND CORROSION

As seen earlier, the major causes of fouling and corrosion are furnace carryover and SO₃ in the exhaust, and therefore, most of the methods are aimed at reducing these components in the exhaust. The problem of SO₃ is common to other systems, such as oil-fired boilers. Several methods of minimizing fouling and corrosion in glass furnace regenerators are briefly discussed below.

Figure 1: A Mechanism of Na_2SO_4 Vapor Condensation Fouling
(Reference 14)

1. Use of Additives: Additives in the melting tank or to the exhaust at various stages react with some of the unwanted components in exhaust to eliminate or reduce their effects.

Injection of magnesium oxide is very effective in neutralizing SO_3 in exhaust. MgO combines with SO_3 to form MgSO_4 , which is a relatively nonreactive compound with high melting point. It deposits on cooler surfaces in the form of a powder which is dry and friable.¹⁹ Another role of MgO is to reduce the catalytic effect of V_2O_5 and iron oxides to convert SO_3 from SO_2 .¹⁹ MgO can be either mixed with the fuel or it can be added to the exhaust as a powder or as a suspension in oil or water.^{4,20} A small amount of MgO (typically 0.025%) in fuel oil can be sufficient.

Addition of a small amount of carbon to the glass ingredients was found to decrease particulates in the exhaust stream very significantly²¹, sometimes more than 50%. Carbon reduces the operating temperature of the melting tank by around 20°C without affecting the glass quality, and is suspected of entering into the glass chemistry resulting in lower particulate concentration in exhaust.²¹

2. Control of Operating Conditions: Controlling of excess air in combustion is a proven technique of reducing SO_3 as well as particulates in the exhaust.^{21,22} Data by Attig and Sedor²² obtained on exhaust of oil-fired boilers show that decreasing excess air concentration from 5 to 1.5 percent lowered SO_3 concentration from 17 to 8 PPM. However, a somewhat contradicting result was reported by Ryder and McMackin²¹ who showed that when the excess air is between 20-25 percent to 30-35 percent (which is more than ordinarily used amount of excess air for combustion in melting tank), the particulate emissions decreased by almost 35%. Outside this range of excess air they did not observe reduction of particulates. It should be noted that reduction of excess combustion air has an adverse effect of increasing NO_x .²¹

In a given glass furnace, increase in the melt tank load can increase the relative amount of particulates as well as SO_2 , SO_3 and NO_x . For example, in a cross-fired gas furnace, the particulates increased from about 5 lbs/hr to 11 lbs/hr with an increase of load from 6 sq.ft/ton to 5 sq.ft/ton.²¹

In general, the operating parameters that affect the important components in exhaust can be summarized as follows²³:

particulates	- melter area, load temperature, excess air
SO_x	- sulfur input, sulfur retention, excess air, particulate emission rate
NO_x	- air to gas ratio, temperature, fuel consumption rate

3. Use of High Quality Fuel: Fuels high in sulfur and other undesirable impurities (such as vanadium) obviously produce combustion gases with high SO_x and other undesirable compounds. However, cleaner fuels (low in sulfur) unfortunately yield less SO_2 , but not SO_3 .¹⁹ For example, a 65 percent reduction of sulfur in fuel decreases the

SO₃ concentration by only 25 percent. Because of the expenses involved, using high quality fuel is not necessarily the most desirable method. Electrical boosting, however, allows reduction in furnace temperature²³ and has no "combustion" products, resulting in cleaner exhaust. It can therefore be used as a partial or total substitution for fossil fuel, if costs permit. Natural gas also is more preferable to oil because of low sulfur and vanadium contaminants.

4. Batch Pretreatment: This includes one or more of following; batch preheating, pelletizing, briquetting, moisturizing, and prereacting. It is a powerful way of reducing gaseous and particulate emissions, and for saving energy. A study conducted by Corning Glass Works on using waste gases to preheat the pelletized batch material showed that it is feasible to reduce the furnace temperature by 500C, capture 80% of SO₂ and 32% of Na₂SO₄ particulates, and significantly reduce NO_x.^{24,25,26} In another study,²⁷ when the batch was moisturized using 3.1% and 5.4% moisture, the furnace carryover reduced by 59% and 64%, respectively, compared to the carryover from dry batch (1.4% moisture). This tremendous reduction in particulate amount in the exhaust was recommended to be worthwhile for the efforts needed for alterations in wet batch handling. Batch briquetting is also expected to reduce particulate concentration.²⁸

SUMMARY

The temperature and composition of exhaust from glass furnaces depend mainly upon the glass type, fuel type, type of furnace, operating temperature, and the location in the exhaust system. The important components of the exhaust from fouling and corrosion point of view are: particulates of Na₂SO₄ (major component), SiO₂, CaSO₄, Al₂O₃, V₂O₅ and cullet dust; and gaseous SO₂, SO₃, NO_x, HCl and HF. The most severe problems in recovering heat from these exhaust gases are fouling and corrosion, which are different in top and bottom zones of regenerators. In the top regenerator, the corrosion and fouling are mainly caused by SiO₂, V₂O₅, brick erosion, and large particulates. In the bottom zone of the regenerator, SO₃ is the major cause of corrosion which acts through the condensed alkali sulfates, and the major cause of fouling is the condensed Na₂SO₄. The typical effects of the fouling and corrosion are: erosion, formation of sticky eutectics, weakening and crumbling of bricks, and deposit of particulates, and slag; consequently, the pressure drop, regenerator brick life and heat transfer are affected. The extent and nature of these effects depend on the composition and temperature of exhaust gases. Several methods have been identified and discussed to minimize fouling and corrosion. They are: (i) use of additives such as MgO and carbon, (ii) control of operating conditions such as excess combustion air percentage and melter tank loading, (iii) use of high quality fuel such as natural gas and electric boosting, and (iv) Batch treatment, such as pelletizing, briquetting, moisturizing, and preheating.

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HEAT EXCHANGERS FOR SECONDARY HEAT RECOVERY FROM GLASS PLANTS
R. L. Webb*, D. Marchiori**, R. E. Durbin⁺, Y-J. Wang⁺⁺, and A. K.
Kulkarni*

ABSTRACT

This paper addresses heat recovery from the exhaust gases leaving the brick checkers regenerator of a soda lime glass furnace. The most desirable uses for the recovered heat are electricity generation and batch preheat. An industry survey indicated that heat exchanger fouling is a primary factor that inhibits use of such heat recovery. For electricity generation, one would use either a Rankine or a Brayton cycle. The former would use a finned-tube heat exchanger, and the latter would use a plate-and-fin exchanger. This paper discusses the fouling, corrosion and cleanability of such heat exchangers in the glass furnace exhaust. The composition of the gases entering the exchanger are described, and the expected fouling mechanisms are discussed. It is concluded that these exchangers should be cleanable, and not subject to excessive corrosion, provided they operate above the acid dewpoint. The use of MgO would further enhance the cleanability of the fouling deposit. The fluidized-bed heat exchanger is an interesting concept for batch preheat. If the concept can be successfully employed, it would be a "self cleaning" heat exchanger.

INTRODUCTION

This paper resulted from a Department of Energy sponsored survey of the glass industry concerning secondary heat recovery from glass furnace gases (1). Kulkarni et al. (2) characterized the exhaust gas composition and the fouling potential in the primary heat recovery "brick checkers" regenerator.

The glass industry consumes 3×10^8 MBtu of energy per year, 80% of which is natural gas. A valved periodic flow regenerator is presently used to recover heat from the melting tank exhaust gases. This regenerator consists of an array of bricks stacked in an "open checkerwork" pattern, through which the exhaust gases and combustion air are alternately passed. The cycle is changed at approximately 20 minutes intervals. The exhaust gas inlet temperature is approximately 2600°F and the outlet temperature ranges from 1500-to-800°F, depending on the number of passes in the "brick checkers" regenerator. Typically used brick checkers designs have gas outlet temperatures of 1000-to-1200°F, which yield air

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preheat temperatures approximately 2000°F, and operate at a thermal effectiveness of 75-to-80%.

Although there is considerable potential for additional heat recovery, glass manufacturers do not employ secondary heat recovery equipment downstream from the checkers regenerator. The key purpose of this study was to identify uses for additional recovered heat, establish the needed heat exchanger types, and identify operating concerns that affect the viability of such secondary heat recovery exchangers. Our industry survey (1) showed that concern over potential gas-side fouling is the key barrier that presently inhibits use of secondary heat recovery equipment.

Because different heat exchanger types may have different fouling characteristics, it is important to establish the candidate heat exchanger types that may be used for secondary heat recovery. This will depend on the selected use for the recovered heat.

HEAT RECOVERY USE VS. HEAT EXCHANGER TYPE

Uses for the Recovered Heat

Four potential uses for additional recovered heat were identified. These are: 1) additional air preheat, 2) steam for process use of space heating, 3) electricity generation, and 4) preheat of the raw materials (batch) fed to the melting tank. There is not sufficient need for steam to justify this possibility. Because the present brick checkers regenerators operate at relatively high thermal effectiveness, a great amount of heat transfer surface would be required to obtain a significant increment of additional air preheat. And, air leakage into the exhaust gases at the regenerator butterfly valve would have a negative effect on such secondary air preheat. The most promising uses for additional heat recovery are electricity generation (cogeneration) and batch preheat. Both of these uses have a relatively low heat sink temperature, so a considerably smaller NTU are required for a given incremental heat recovery than would be required for the additional air preheat option. The inlet heat sink temperatures for cogeneration and batch preheat are approximately 500°F and 80°F, respectively.

Table 1 presents a matrix of the possible uses for additional recovered heat vs. candidate heat exchangers. The remaining discussion will be limited to heat recovery for cogeneration and batch preheat.

Cogeneration

In a cogeneration system, the hot exhaust gases provide the heat input to a power generation cycle. The turbine drives a generator, which provides electricity for plant use. Two basic types of power cycles may be considered: 1) a Rankine cycle using steam or an organic working fluid, or 2) a Brayton (gas turbine) cycle, which uses air as the working fluid. These cycles will use different types of heat recovery exchangers. The Rankine cycle normally employs a bare or finned tube bank, with the exhaust gases in crossflow over the outer tube surface. The Brayton cycle proposed by AiResearch (9) uses a

Table 1: Candidate Heat Exchangers for Secondary Heat Recovery Applications

Heat Exchanger Type	Used for Recovered Heat			
	Air Preheat	Steam Generation	Cogeneration	Batch Preheat
Checkers Regen.	X			
Rotary Regen.	X			
Finned-tube	X	X	X	
Plate-and-Fin	X		X	
Static Bed				X
Fluidized Bed				X

plate-and-fin exchanger; this heat exchanger construction is illustrated by Figure 1. The envisioned Brayton cycle uses the exhaust gases to heat compressed inlet air, which is then expanded through the turbine to approximately atmospheric pressure. The hot turbine exhaust air is ducted to the checkers regenerator as preheated air. Hnat (3) provides an excellent description of these heat recovery cycles, and provides analysis of their system performance.

The finned-tube and the plate-and-fin exchangers are widely used in commercial practice, although they have not been applied to heat recovery from glass furnaces. Glass industry personnel are very concerned about their fouling potential.

Fig. 1 Crossflow plate-and-fin heat exchanger, with illustration of the "offset strip-fin".

A fluidized-bed heat exchanger may be considered as an alternate to the "indirect contact" exchangers discussed above. The medium to be heated would pass through horizontal tubes immersed in the fluidized bed. Graded glass cullet may be an acceptable bed material. The hot exhaust gases would enter at the bottom of the bed, via a distributor plate, and "fluidize" the bed particles. The scouring action of the particles will prevent the formation of a foulant deposit on the heat exchanger tubes. The Na_2SO_4 particulates would be entrained from the bed. Such a concept would be "self-cleaning" heat exchanger. However, a penalty must be paid, in terms of fan power required to fluidize the bed. To date, this concept has not been tested.

Batch Preheat

This may be obtained by passing the exhaust gases through a fluidized bed or a static-bed heat exchanger. Used here, the hot exhaust gases would fluidize pelletized batch materials. The use of batch preheat would alleviate the need for other secondary heat recovery uses. This use of recovered heat would yield furnace energy savings of approximately 20%. Sakhuja and Cole (4) discuss a program to develop this concept.

GAS COMPOSITION LEAVING THE REGENERATOR

A secondary heat exchanger will be supplied with the 1000-to-1200°F gases that leave the regenerator. In addition to CO_2 , N_2 , O_2 and H_2O vapor, these gases contain particulates and condensible vapors that are the cause of fouling, and may cause corrosion of the heat transfer surface. Tables 2 and 3 give the composition of the particulates and the contaminant vapors, respectively for soda-lime glass manufacture.

Table 2: Composition of particules leaving the regenerator (5)

Concentration (ppm by weight)	200
Size	90% < 4 μm
Chemical Composition (% by wt.)	
Na_2SO_4	90%
K_2SO_4	3%
CaSO_4	4%
SiO_2 , Al_2O_3 + Others	3%

Table 3: Composition of vapor contaminants leaving the regenerator (5, 6)

Composition	Gas Fired ppm (by wt.)	Oil-Fired ppm (by wt.)
SO ₂	10 - 80	up to 270
SO ₃	0 - 5	5 - 30
NO _x	400	400
HCl	15	15
HF	1.5	1.5

FOULING AND CORROSION MECHANISMS

Kulkarni et al. (2) have shown that severe chemical reactions and fouling exists within the regenerator. The reaction of the volatile elements, and their subsequent condensation and solidification yield a slag or particulates that solidify at 1623°F (884°C). The fine, solid particulates listed in Table 2 are the main source of fouling in a heat exchanger downstream from the regenerator.

As the gases listed in Table 3 pass through the heat exchanger, two chemical reactions are possible that may cause corrosion, and further contribute to surface fouling.

A "hot end" corrosion reaction may result from the reaction of K₂SO₄ or Na₂SO₄ with SO₃ (7). The reaction products are corrosive liquid pyrosulphates (K₂S₂O₇ or Na₂S₂O₇); these pyrosulphates solidify at 765 and 754°F, respectively. The liquid pyrosulphates will tend to entrap the Na₂SO₄ particulates. As the surface temperature is lowered, the deposit dries to a hard scale, which is quite difficult to remove by air lancing. But, it is water soluble and can be removed by water washing (8). Ref. 7 presents data, which show that SO₃ concentrations above 150 and 2200 ppm are required to form K₂S₂O₇ and Na₂S₂O₇, respectively. However, AiResearch (9) concluded that Na₂S₂O₇ was formed with 27.6 ppm SO₃ concentration (by weight).

A "cold end" corrosion reaction will occur if the H₂SO₄ formed by reaction of SO₃ and H₂O vapors condenses. The dewpoint of the H₂SO₄ depends on the SO₃ concentration (6). It is also possible for the condensed acid to react with Na₂SO₄ to form Na₂SO₇. And, if the water vapor also condenses, NaHSO₄ will be formed. These condensates form a "sticky" surface which entraps the Na₂SO₄ particulates. The resulting deposit may be removed by steam or water wash (6).

The addition of MgO to the flue gases will act to consume the excess SO₃ forming MgSO₄. This will be beneficial for both the hot and cold corrosion and fouling situations. If the "sticky" condensates can be prevented, the surface fouling problem will be greatly alleviated. The resultant deposits are dry, soft and can be removed by air lancing or steam soot blowers (10).

HEAT EXCHANGER FOULING AND CORROSION

The previous discussion has established that the fouling/corrosion characteristics of finned-tube and plate-and-fin heat exchanger types are of interest. Our glass industry survey (1) showed that there is very little use of the proposed secondary heat recovery methods. Discussions with engineering personnel indicated that fouling is a major impediment to the use of secondary recovery heat exchangers. The previous discussion suggests that the fouling and corrosion potential for a secondary recovery heat exchanger is much less severe than that of the checkers regenerator. However, the use of MgO addition, and avoidance of "cold end" corrosion and fouling suggests that the foulant is removable by conventional methods.

Our study showed that fouling and corrosion data exist on the following heat-exchanger geometries supplied with gases downstream from the checkers regenerator: 1) Fin-and-tube: Only proprietary data were found (8). 2) Bare tubes used in water-tube and fire-tube boilers (10); 3) Plate-and-fin: a very thorough study using several surface geometries in a simulated glass furnace exhaust (6,9).

Although no data exist for finned-tube exchangers in a glass furnace exhaust, this geometry has been widely used for economizers in oil and gas-fired water-tube boilers, and has been evaluated for heat recovery from diesel engine exhausts (11,12). In these applications the gas temperature entering the heat exchanger is 450-to-750°F, and the gases contain "soot" particles of a size comparable to the dust from glass furnace regenerators. Comparable fouling mechanisms would be expected in the glass furnace, boiler and diesel applications, e.g., particulate fouling at the hot end, and moisture condensation, plus particulate fouling at the cold end.

Plate-and-Fin Fouling/Corrosion Tests

AiResearch has measured the fouling characteristics of the Figure 1 plate-and-fin geometry using a simulated glass furnace exhaust (6,9). The geometries tested are listed in Table 4, and include 3 and 7.5 fins/in. plain fins, and 5 and 6.5 fins/in. offset strip fins (Fig. 1). A cross-flow exchanger was used with the hot gases on one side, and air on the coolant side. The hot gases were composed of natural gas combustion products with dilution air, and the following added contaminants (ppm by weight): SO₂ (200), SO₃ (27.6), and HCl (16). The particulates were taken from an operating glass furnace. Their size distribution was $11 < d < 75 \mu\text{m}$, which is considerably larger than the distribution given in Table 2. The fouling rates were defined by the measured pressure drop. All test cores had 4.5 x 6 in. gas-side frontal area and were 12 in. deep.

Two cleaning techniques were tested: 1) A traversing air lance consisting of a series of small holes drilled along the axis of a tube, and 2) An "air cannon", which uses a sudden discharge of a large quantity of high pressure air. The air lance provides a line array of high velocity air jets which discharge directly onto the flow passages, at the upstream exchanger face. Each jet discharges 1.3 lbm/hr through a 0.045 in. orifice.

Table 4: Plate-and-fin Geometry Parameters Tested by
AiResearch (6)
(* Based on total $4.5 \times 6 \text{ in}^2$ frontal area)

Heat Exchanger Identification	Fin Height, in.	Fin Thickness, in.	Fin Density, fins/in.	Offset Length, in.	Frontal Gas Velocity * ft/sec
1	0.55	0.016	3	Plain	31.3
2	0.55	0.016	6.5	0.5	21.2
3	0.145	0.016	7.5	Plain	24.0
4	0.145	0.016	5	0.178	19.2
5	0.29	0.016	7.5	Plain	26.1
6	0.29	0.016	5	0.178	20.9

"Hot End" Fouling Tests

These "accelerated" fouling tests (6) used 1,250°F gas inlet temperature, 300°F inlet air, and incident gas velocities of 19-to-31 ft/sec. The gas velocities are equal to those that would be employed in a Brayton cycle heat exchanger. A 1600 ppm dust concentration was used, which is 8-times the value given in Table 2. Figure 2 shows the fouling data for plain fin surface 3 and offset strip fin surface 4 (Table 4). The 300 psi air lance, operating at approximately 10-hour intervals successfully cleaned the 7.5 fins/in plain fin surface, but was ineffective for the 5 fins/in offset strip fin.

Fig. 2 Fouling rate and cleaning characteristics of the plate-and-fin exchangers using 1250°F gas inlet temperature, 300°F outlet and 1600 ppm particulate loading (6).

AiResearch performed further experiments with the Table 4, geometry 3, using 200 ppm particulate loading (9), and investigated the effect of SO₃ concentration and metal temperature on the cleanability of the deposit. Deposits on the back face of the exchanger were removed and chemically analyzed for acidity (pH) and Na₂S₂O₇ content. Using titration and x-ray diffraction analysis, it was concluded that the deposits contained significant amounts of Na₂S₂O₇, but no NaHSO₄. The metal temperatures, corresponding to these deposit locations, were measured with thermocouples. The results of these tests are shown in Figure 3. This Figure shows that the deposit in the examined channels was not cleanable if the deposit pH < 2.5; this pH corresponds to 20% Na₂S₂O₇. These data were used to establish minimum metal temperatures, for which the deposit pH > 3, and the channels are cleanable with the air lance. It is noted that Reference 7 indicates that Na₂S₂O₇ should not have been formed for these gases, which contained SO₃ concentrations of 27.6 ppm (wt.), or less. This test series showed that the air lance will restore the pressure drop of the 7.5 fins/in plain fin geometry to its initially clean value. The exchanger pressure drop increased approximately 40% during the six-hour period between cleaning cycles.

A similar fouling behaviour was observed by Hannaken (8) in their tests of the studded fin-and-tube geometry illustrated in Figure 5. The tests were conducted using regenerator exhaust gas, and cooling oil on the tube-side. The character of the foulant was dependent on the tube surface temperature, as given below:

Fig. 3 Plate-and-fin cleanability as a function of SO_3 concentration (by vol.) and metal temperature (9).
ppm wt. = 2.76 ppm vol.

Fig. 4 Recommended minimum metal temperatures to avoid the hard scale fouling deposit, based on $\text{pH} > 3$ (9).

Fig. 5 Studded fin geometry on 2 in. diameter tubes tested by Hannaken (8).

1. 869°F gas temperature without heat transfer: the deposit consisted of a very thin coating of fine powder, which was easily removed.
2. 760-to-930°F gas temperatures, with 500°F tube temperature: a 1/8" thick dense powder deposit. An air lance removed "most of the deposit".
3. 650-to-860°F gas temperature, with 300°F tube temperature: the tube surface was coated with a 0.005/0.010 in. thick hard scale. On top of this was a 1/4" thick layer of soft yellow powder. The air lance removed only the outer soft layer. The hard scale was removable with a water wash.

"Cold End" Fouling Tests

These AiResearch tests (6) were conducted using 1000°F gas inlet, and at 100°F air inlet, which assured moisture condensation. Data were obtained for the 7.5 fins/in. plain fin geometry of Table 4 using 12 ft/sec. air velocity and 200 ppm dust. Two test series were run: 1) with water and acid condensation, and 2) acid condensation only. In both tests, a condensate-particle sludge formed, which plugged the flow passages. The exchanger core was not cleanable with either the air lance or air cannon. The greatest fouling rate occurred for acid condensation only. Significant corrosion was observed on the 409 stainless steel fins.

Finned-Tube Fouling Data

Fouling data on finned-tubes in glass furnace exhausts are not reported in the literature. Proprietary tests of the Figure 5 studded-fin have been noted.

We have suggested that finned-tubes used for heat recovery from gas-turbine and Diesel exhausts may experience similar fouling mechanisms to those of a glass furnace exhaust. Roberts and Kubasco (12) measured fouling on a bank of helical-finned tubes in the exhaust of a gas turbine. The tubes were 3/4 in. diameter with 7 fins/in., approximately 3/8 in. fin height. The tubes were exposed to 850°F exhaust gases, and the fin temperatures were 300-to-600°F. The deposits were "fluffy" and easily removed by air lancing. The deposit thickness increased as the metal temperature was decreased. Analysis of the deposit suggested a "two-stage mechanism of soot build-up". Trace quantities of hydrocarbons condense on the surface forming a thin coating of an adhesive nature. Particulates are trapped by this coating. A "self-cleaning" method was evaluated, in which coolant flow to the tube-side was stopped, and the hot gases acted to "bake off" the deposit. The "threshold" temperature for self-cleaning was found to be between 670 and 785°F.

Silvestrini (13) measured "cold end" fouling and corrosion on 1.25 in. diameter 3 and 5 fins/in. tubes in the 400-to-500°F exhaust of a Diesel engine. The test compared fouling on uncooled tubes with that on cooled tubes (220°F wall temperature). The acid condensation temperature was 242°F. "No measurable soot accumulation was observed on any of the uncooled tubes." However, the cooled tubes exhibited severe fouling and plugging.

These studies show a consistency with the glass exhaust studies in several respects: 1) Fouling is dependent on the wall temperature and the surface-to-gas temperature difference. 2) If vapors do not condense, an easily removed fluffy deposit occurs. In the limiting case of zero heat transfer, the particulate deposit is of negligible thickness. 3) Above the acid and water vapor dewpoints, some vapors may condense. These yield a hard deposit on the tube surface that is difficult to remove by air lancing. However, it may be washed away with water. 4) Below the acid and water dewpoints, the deposit is sticky and cannot be removed by air lancing, although it may be water washed.

Heat Transfer with Bare Tubes

Richards (10) discusses operational experience with three glass plant waste heat boilers in Europe. The glass furnaces are fired with heavy oil (0.8-to-1.8% sulphur). All boilers have plain tubes, use MgO addition and are soot blown once per shift. Table 5 gives particulars for each installation.

Table 5: Waste Heat Boiler Installations

Type	Unit 1 Water tube	Unit 2 Fire tube	Unit 3 Water tube
Gas inlet (F)	860	968	720
Gas outlet (F)	531	608	536
Tube-side (F)	560	572	150
Tube dia (in)	2.5	2.5	1.25
Number of tubes	900	1312	124
Soot blower	Steam	Steam	Air

All boilers had been in operation two years or longer, and satisfactory operation is reported. Richards states that $\text{Na}_2\text{S}_2\text{O}_7$ would be formed if MgO injection were not used. The MgO consumes the SO_3 , and negates the possibility of $\text{Na}_2\text{S}_2\text{O}_7$ formation. The foulant deposits are "dry, friable, and can be removed by sootblowers".

Finned-Tube Vs. Plate-Fin Designs

It is interesting to speculate on the relative fouling rates of these two exchanger types, and their cleanability.

The plate-and-fin geometry has a constant area flow channel, and no stagnation or separated flow zones within the fin passage. But, a stagnation region exists at the front face of the heat exchanger. One would expect a relatively uniform fouling deposit in the fin channels (as would occur for a fire-tube boiler design). However, plugging will occur on the front face of the exchanger, as observed in the AiResearch tests. The AiResearch reports do not define how the pressure drop increase was apportioned between fouling at the face of the exchanger, and in the flow passages. Soot blowing will affect foulant removal as a result of high shear stress at the fin surface. Therefore, one would expect

this high velocity will be quite effective over the entire finned surface area.

The finned tubes experience a stagnation/accelerating flow on the upstream half of the tube, and a decelerating flow with flow separation on the downstream half of the tube. Because the surface shear stress is greater on the front half of the tube, one may expect smaller fouling deposits on the upstream face. This is precisely the foulant deposit pattern observed by Kindlman and Silvestrini (13) for heat recovery from Diesel exhaust with acid condensation. The fouling deposit thicknesses at the fin-tip for the upstream and downstream faces are shown by Figure 6. When the sootblower is operated, the smallest local surface shear stresses will occur on the downstream face - where the greatest foulant deposit exists. Thus, the desired cleaning shear stress distribution is opposite to the desired distribution.

Fig. 6 Fouling thickness near the fin tip on 1 1/4 in. diameter tubes with 3 fins/in., 5/8 in. fin height (13)

The above observations suggest that the plate-and-fin design will make better use of the soot blower momentum, and will experience relatively uniform cleaning. If this evaluation is correct, it is interesting to further speculate on alternate fin-and-tube geometries that will experience the favorable cleaning characteristics of the plate-and-fin design. One possibility is to employ a counterflow exchanger having longitudinal external fins on the gas-side.

CONCLUSIONS

1. If the acid condensation regime is avoided, it appears that finned-tube and plate-and-fin geometries can be successfully applied to glass secondary heat recovery applications.
2. The conditions for which alkali-pyrosulphates are formed and condensed are not clearly understood. Their formation apparently yields a hard scale at reduced wall temperatures. Figure 5 suggests minimum metal temperatures that will avoid the hard scale.

3. The use of MgO addition will avoid the pyrosulphate formation, and the fouling deposit will be fluffy, and cleanable.
4. Present fouling data suggests that plain fins should be used.
5. The permissible fin density will depend on the desired cleaning frequency. The AiResearch plate-and-fin data (6,9) suggest that 5 fins/in. would not require cleaning more than once per shift. There is no experimental basis to recommend a maximum fin density for a finned-tube exchanger.
6. Fluidized-bed heat recovery systems offer the possibility of secondary heat recovery, without the fouling problems associated with conventional heat exchangers.

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RESEARCH AND DEVELOPMENT NEEDS

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The primary objective of this Department of Energy supported project was to identify R&D needs that will advance the use of secondary heat recovery in the glass industry. Based on our discussions with glass industry personnel, we have identified three key topics, which address heat exchanger technology related to heat recovery from the glass furnace, or the regenerator exhaust gases. All projects envision significant energy savings, and involve heat exchange technology not presently used in the glass industry.

I BATCH PRETREATMENT

Introduction

Several studies (1-7) have shown that moisture addition and agglomeration of the raw batch will yield reduced particulate carry-over and reduced SO_3 , in addition to furnace energy savings. More recent studies have shown that preheating of the pelletized or briquetted batch will yield energy savings on the order of 20%. Laboratory studies of a static bed preheater using simulated furnace exhaust gases showed (2):

1. 20% energy savings
2. 32% capture of Na_2SO_4 particulates
3. 80% capture of SO_2
4. 65% reduction of NO_x
5. 100% increase of glass tank melting capacity

The one disadvantage of this pretreatment is the cost of producing the pellets or briquettes (\$1.50-to-\$2.00/ton). Although batch preheat promises excellent pollution, energy, and other operational benefits, it is not commonly used today.

Preheat of the batch would raise its temperature to approximately 1,500°F. Secondary heat recovery from the 1,000-1,200°F regenerator exhaust gases would supply approximately 50% of the batch preheat energy requirement.

From a heat exchange technology point of view, the key R&D need is the evaluation of the heat exchange concept between the regenerator exhaust gases, and the batch. Both static bed (2) and fluidized bed (3) heat exchangers have been proposed.

Objective

Establish feasible concepts for heat exchange between the batch and the regenerator exhaust gases.

Description

Three project tasks are envisioned:

1. Propose heat exchange concepts, and establish the possible physical configurations of the batch, e.g., raw, pelletized or briquetted. Establish the effect of the processing on pollutants and particulate carryover of the batch preheater and the glass furnace exhaust gases.
2. Conduct pilot scale tests of the proposed heat exchange concepts, and evaluate the effects of operational parameters. Measure the pollutant and particulate concentrations and composition of the gases leaving the preheater and the glass furnace.
3. Establish energy savings, pollutant reduction, and cost effectiveness of the preferred heat exchange concept.

II. HEAT EXCHANGER TECHNOLOGY

Introduction

Throughout the glass industry, essentially no heat recovery is presently used downstream of the brick checkers regenerators. Flue gases at 1000 to 1200°F are presently exhausted to the atmosphere. Several heat recovery systems are available to provide additional energy savings downstream of the brick checkers regenerators. A major barrier to acceptance of this equipment is the concern that heat exchanger fouling will render these systems inoperative. A program is therefore needed to define the preferred exchanger geometry and fin spacing, and the cleanability of the heat exchangers used downstream of the brick checkers regenerator.

Objective

1. Determination of the fouling rates for tube-fin and plate-and-fin heat exchanger geometries in a simulated glass furnace exhaust stream.
2. Establish an analytical model to predict the fouling rate as a function of the operating parameters.
3. Determination of the cleaning frequency required to keep the mass flow rate through the candidate heat exchanger geometries within glass processing limits.

Description

1. Test conditions.

- a. Inlet exhaust gas temperature: 1000 to 1200°F
- b. Exhaust gas temperature range
 - 1) 1200°F to 350°F
 - 2) 100 to 200°F increments
- c. Inlet exhaust gas velocities typical of a full scale heat exchanger unit
- d. Simulate soda-lime glass exhausts with and without MgO injection

2. Heat exchanger geometries

- a. Tube-fin geometry - plain fins
 1. fin density: 0-to-5 fins/inch
 2. tube O. D.: 0.75-to-2.5 in.
 3. tube spacing: $x_t/d_o = x_f/d_o = 1.1$ -to-2.0
 4. fin height: 1/4"-to-1 1/4"
 5. materials - compatible w/ glass exhaust
- b. Stacked plate-fin geometry
 1. fin density: 2-to-6 fins/inch
 2. fin height (gas side spacing): 1/4"-to-1/2"
 3. materials - compatible w/ glass exhaust

3. Cleaning methods to be evaluated

- a. Air lance
- b. Steam lance
- c. Air cannon
- d. Sonic cleaning

III. NON-FOULING HEAT EXCHANGERS

Introduction

As pointed out earlier, the major (and sometimes the only) concern of glass manufacturers in not attempting additional heat recovery from the exhaust gases (typically at 1000-to-1200°F) is the problem of the fouling of heat exchanger surfaces. Naturally, a "non-fouling" heat exchanger is desirable, if it is cost-effective. From this point of view, fluidized bed and fixed (recycled) bed type heat exchangers seem to offer a great promise. The basic idea is as follows: The exhaust from a glass furnace (~2500°F) or from the downstream of checker units (~1000°F) is passed through a shallow bed of particles, which may be made up of ceramic or steel balls of up to 4mm in diameter, or just plain sand. In this bed of particles, plain or finned tubes carrying secondary heat transfer medium such as air, water, or steam are embedded. The bed of particles is heated by hot gases and the heat is transferred to embedded tubes by recirculating particles in direct contact with the tube. There are three major advantages of this type of heat exchanger: (1) Because of the particle recirculation, the heat transfer tubes are continuously scoured and cleaned, so that foulant deposition on the tubes is practically

absent. (2) The same process renders extremely high heat transfer rates, typically 150 - 500 W/m²K, which are 3 to 20 times the conventional heat transfer rates. (3) And finally, the foulant in the exhaust gas stream is expected to be trapped in the bed material (as opposed to being deposited onto the heat exchanger surface), which is probably easy to remove. Although this concept is new for the waste heat recovery in the glass industry, heat exchangers of this type have been attempted for other applications; for example, in heat recovery from geothermal water, heat recovery from natural gas or oil combustion exhausts in some industries, waste calcination, waste heat disposal, grain drying, coal combustion, etc. In the glass industry, apart from recovering heat for other uses, one may preheat the batch material using it as the bed medium itself.

Objective

1. To study the feasibility of using a fluidized bed or fixed recycled bed heat exchanger for heat recovery from glass industry exhaust gases.
2. To determine the optimum design configuration for this type of heat exchanger.
3. To study foulant removal methods in these configurations.

Description

The proposed project of exploring the use of particle bed-type heat exchangers for the heat recovery from the glass industry exhaust is novel, involves high risk, and needs advanced technology and concepts - and therefore has a potential for offering unprecedented results. An initial project would include the following four tasks:

1. Make a thorough study of designs and operation of currently used fluidized and static bed heat exchangers.
2. Make a rough estimate of possible cost effectiveness.
3. Construct an experimental set-up to determine optimum design conditions by varying the following parameters:
 - a. bed material parameters, such as particle size, type of material, etc.
 - b. hot gas flow rate and bed temperature.
 - c. heat transfer tube geometry parameters, plain and finned tubes, their configuration (horizontal or vertical), etc.
 - d. single pass and multipass beds.
 - e. heat transfer medium: water, air, and batch material itself.
4. An important part of the project should be the study of methods to remove foulants trapped in the bed material.

Some of the possibilities are:

- a. Use the mixture of the initial bed material and the trapped foulant as the bed material itself, then remove the bed material continuously to maintain the desired bed height.
- b. Discard the bed material completely at constant intervals.
- c. Continuously remove the bed material, clean it, and reuse.

Related Work

References 8 through 16 give a general idea of some of the previous work done in the area of waste heat recovery by fluidized bed heat exchangers. These studies were not carried out specifically for glass furnace exhaust, however, they are indicative of the potential for glass industry application. Technical information contained in these and several other references will be extremely valuable as the background and experience for further research and development of fluidized bed heat exchangers for waste heat recovery in glass industry.

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