INDUSTRIAL HEAT EXCHANGERS

Edited by A. J. Hayes, W. W. Liang, S. L. Richlen and E. S. Tabb

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Editor's Foreword

The 1985 Exposition and Symposium on Industrial Heat Exchanger Technology was a jointly sponsored effort by the American Society for Metals, the Gas Research Institute, and the U.S. Department of Energy. The goal of the Symposium was to provide a forum for the exchange of information about industrial heat exchanger technology. The Symposium Sessions covered the span of heat exchanger technology including configurations, new materials, field test results, thermal performance, corrosion, and economics. Symposium participants included heat exchanger researchers, manufacturers, and the industrial users.

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W. W. Liang
S. L. Richlen
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TABLE OF CONTENTS

SESSION I: THE INDUSTRIAL USERS POINT OF VIEW; THE DOE AND GRI PROGRAMS -INTRODUCTION-

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It is critical that the heat exchanger manufacturer be aware of the perspective of the potential heat exchanger user and the development programs of the U.S. Department of Energy and the Gas Research Institute. The needs of the potential user, even if they are only perceived needs, must be addressed if new heat exchanger technology is to be successfully marketed. To support this awareness, the perspective of major industry is presented in this session.

There are two major funding organizations currently developing advanced industrial heat exchanger technology to provide greater efficiencies at lower cost. Both the heat exchanger manufacturer and the potential user need to stay informed of these technology developments so they can be promptly implemented. Both the Department of Energy and the Gas Research Institute Programs are described in this session so the user and manufacturer can be informed of the goals and directions of these programs.

HEAT EXCHANGE IN THE STEEL INDUSTRY

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Abstract

A brief historical perspective of steel industry use of heat exchange equipment is presented and the current status, requirements and potential for the use of heat exchanger equipment in the steel industry are discussed. Factors to consider in the development of heat exchanger equipment for the steel industry are described.

THE STEEL INDUSTRY is a major user of heat exchanger equipment. As a start for this symposium on Industrial Heat Exchanger Technology, this paper presents a brief historical perspective of steel industry use of heat exchange equipment, and the current status, requirements and potential for the use of heat exchange equipment in the industry.

HISTORICAL PERSPECTIVE

The subjects of heat exchange and steel production have been closely interwoven since the beginning of the industrial revolution. During the 19th Century, heat exchanger developments and the concept of the use of preheated air were key innovations that made possible economical, high volume production of hot metal from the blast furnace and steel from the open hearth processes.

In the case of the blast furnace, J. B. Neilson in Scotland patented in 1828 the concept of the blast furnace stove which was coal fired to preheat the air blast to 350°C (1)*. Significantly, history records that by 1835, only seven years after issuance of the patent, Neilson's method had been generally adopted with up to 70% reduction in fuel consumption. Another benefit that resulted from the use of the preheated blast was that lower grade ores could be smelted more efficiently than with a cold blast.

Neilson's development was followed in 1868 by the first commercial production of open hearth steel utilizing a reverberatory furnace developed by Frederick and William Siemans. Incorporated into this furnace was their development of regenerative preheating of the combustion air using the heat from the hot combustion gases. This development achieved the very high furnace-temperature needed to melt pig iron and scrap.

Since these early efforts, continued advances in heat exchanger technology have been applied to all phases of steel production and processing. Figure 1 shows a flow sheet for a state-of-the-art integrated steel mill. (2) For such a mill in the United States, the heat exchanger applications listed in Table 1 are commonly associated with the coke oven, blast furnace, soaking pit and reheating processes. Despite these advances however, production of steel products by integrated producers today requires 31-35 MJ/kg (27-30 MMBtu/ton), and energy costs represent approximately 28-30% of steel manufacturing cost in the United States. Significant improvements in heat exchange technology and associated waste heat recovery methods, therefore, continue to be introduced into the steel industry world wide and further advances can be expected.

OVERVIEW

A brief look at the economics of waste heat recovery indicates the potential that remains for energy cost reduction in the steel industry. As listed in Table 1, a commonly used method for waste heat recovery is recuperation. A conceptual diagram of a recuperator is presented in Figure 2. With recuperation, the basis for energy savings is that heat is continuously recycled from the waste exhaust gases to preheat the incoming combustion air and/or fuel. This process results in a lower overall waste gas temperature leaving the system and a reduced fuel and air input to the process. Hence, recuperation results in a

*Numbers in parentheses refer to bibliography at end of paper.

reduction of both the waste gas temperature and the waste gas mass flow rate.

The energy savings from recuperation can be determined by performing an energy balance. The percent energy savings can be calculated given the waste gas temperature leaving the process and the preheated combustion air temperature. If this procedure is repeated for a number of waste gas temperatures and combustion air temperatures, a graph can be prepared that shows the percentage energy saved versus the preheated air temperature and the waste gas temperature. Such a graph for a natural gas fired furnace is shown in Figure 3 (3).

The present status of the use of reheat furnace recuperation in the steel industry in the United States was recently investigated by W. E. Brennen, Inc., management consultants of Evanston, Illinois (4). Typical data for the recuperation practices of companies surveyed are tabulated in Table 2. This investigation concluded that:

1. 95% of existing reheat furnaces have recuperators.

2. Commonly used recuperator types and suppliers are:

Tubular:	Thermal Transfer
Hazen:	C/E Air Preheater Division
Stack:	American Schack
Escher:	Rust Furnace Co.

3. Flue gas temperatures vary from 815 to 1260°C (1500 to 2300°F) diluted and from 1090 to 1320°C (2000 to 2400°F) undiluted.

4. Combustion air preheat temperatures vary from 230-480°C (450-900°F).

5. Major materials used in recuperators are 300 and 400 series stainless steels. Non-ferrous based alloys represent only 5-10% of all materials used.

Taking these data as a base and referring back to Figure 3, the economic potential for significant improvement in recuperation waste heat recovery is apparent. Using typical values for present day practice, 1200°C (2200°F) flue temperature and 370°C (700°F) combustion air preheat temperatures, Figure 3 indicates current fuel savings of approximately 28% are being achieved. If the combustion air preheat can be increased an additional 220C (400F) to 590°C (1100°F), the potential fuel saving percentage would be 38%. Based on natural gas priced at 3.79 \$/GJ (4.00 \$/MMBtu) and a present annual reheat furnace energy usage of 0.3×10^9 GJ (0.28×10^{15} Btu) (3) the potential additional annual saving for the U.S. steel industry would be:

$0.14 \times 0.3 \times 10^9$ GJ/Y x 3.79 \$/GJ = \$159 million/year

Achieving these savings, however, may require the use of upgraded alloy materials.

In addition to energy savings a recuperator also can provide productivity benefits. If a process is constrained by either fuel, combustion air or waste gas flow rate, a recuperator may increase productivity since it reduces the capacity requirements for all of these flows.

Offsetting potential cost savings is the cost of recuperation. The primary cost consists of the recuperator and supporting equipment and installation costs. With a good recuperator design, operating and maintenance costs are generally negligible compared with the equipment and installation costs. In general, the cost of recuperation depends on factors such as (1) alloy content of the recuperator materials; (2) recuperator size, complexity, configuration; and (3) whether or not the recuperator is being installed in a new facility (greenfield) or as a retrofit (existing facility).

In the case of new facilities, expenditures to accomplish energy savings can be justified on the incremental cost of incorporating the energy savings equipment. In retrofitting to existing processes, the full cost of the heat exchanger and support equipment often has to be justified unless the retrofit is part of an extensive rebuild program. Other constraints encountered with retrofit applications include (1) size and space (layout) constraints, (2) fuel type constraints, and (3) auxiliary equipment constraints. These constraints generally substantially increase the cost of achieving the energy savings. For retrofit applications, any production loss during the installation period also is another potential cost. Recuperators, however, often are installed during major overhauls when the facilities are out of service for repairs. For these cases, no unusual production loss is incurred.

Inland Steel's No. 3 Continuous Anneal Line (CAL) is a good example of what can be accomplished with a new facility. (See Figure 4.) In this facility, three waste heat recovery loops are incorporated:

- Loop 1 Radiant tube combustion products are utilized to preheat the incoming strip to a temperature of approximately 180°C (350°F).

- Loop 2 Recuperator burners are used on 292 natural gas fired radiant tubes to achieve 370°C (700°F) combustion air preheat. Each burner's capacity is 320 MJ/h (3×10^5 Btu/h).

- Loop 3 Hot water from the quench tank is utilized in the hot water rinse section.

With these features, even with two heating furnaces (high and low temperature anneal) energy consumption of this line is less than that of older continuous anneal lines which incorporate only one heating furnace.

Current new facility programs in the United

States steel industry are centered mainly on expansion of continuous casting capacity and finishing processes such as strip electro-galvanizing. These facilities do not involve high temperature combustion processes and, therefore, the greatest potential for installation of high temperature recuperation and heat exchange equipment is in the retrofit category. The list of candidate retrofit applications includes:

1. Waste heat recovery in the slot oven coking process from the coke oven gas and underfiring flue gases.
2. Recovery of waste heat from sinter plant strand flue gases, sinter cooler air and recuperation for preheating combustion air and fuel in the ignition furnace.
3. Waste heat recuperation for preheat of blast furnace stove combustion air and fuel gas.
4. Higher temperature recuperation for soaking pits.
5. Higher temperature recuperation for reheat furnaces.
6. Intermediate and high temperature burner recuperators for combustion air preheat in batch anneal furnaces.
7. Higher temperature recuperators for radiant tube combustion air preheat in continuous heat treating lines.

For such applications, the steel industry's requirements can be divided into two distinct categories: economic requirements and practical requirements. Each of these requirements is discussed next.

ECONOMIC REQUIREMENTS

In general, economic benefits can be accomplished by designing recuperator systems to:

1. Maximize the equipment life.
2. Maximize the energy cost savings.
3. Minimize the equipment capital costs.

Obviously, all of the above items cannot be optimized simultaneously; hence, trade offs have to be made. The various factors and trade offs affecting current recuperator performance and the economics of recuperation are discussed below.

RECUPERATOR COST/ENERGY SAVING TRADE OFF - One of the principal factors affecting both cost and savings is the recuperator size or heat transfer surface area. Increasing the size of a recuperator will increase the preheated air temperature and energy savings but will also increase costs. Hence, a trade off exists between energy savings and recuperator costs. If the capital costs (equipment and installation costs) of the recuperator are amoritized over the life of the recuperator, the general framework for this trade off can be depicted graphically as shown in Figure 5.

The explanation for Figure 5 is as follows. In general, as recuperator size is initially increased, fuel costs will decrease faster then recuperator costs increase. At some preheat air temperature point, recuperator materials and combustion air piping materials need to be upgraded--introducing a discontinuity into the cost curve. As recuperator size continues to be increased, recuperator costs eventually increase faster than fuel costs decrease and diminishing marginal returns result. For many applications, an optimum design point can be identified which will provide the lowest overall system cost. When such an optimum can be identified, the system should be designed to these optimum conditions.

Besides being optimized, the recuperator system must provide an acceptable return on the investment. Just because a system has been optimized does not mean that an acceptable return will result. Currently, a 32% internal rate of return is used by many companies as a minimum acceptable return in order for a project to be approved.

RECUPERATOR LIFE - Economic considerations favor long recuperator lives and, in general, recuperator lives in excess of 10 years are preferred. For a recuperator to provide long service life, conservative designs* are required which adequately allow for the principal failure mechanisms. The principal failure mechanisms of metallic recuperators include:

1. Excessive stress (especially due to thermal expansion).
2. Creep.
3. Thermal Fatigue.
4. High temperature gaseous corrosion.

These principal failure mechanisms are compounded by a phenomenon known as secondary combustion. When a recuperator develops a leak,

*There are good reasons for advocating that a recuperator be designed conservatively. For example, it is reasonable to expect that a recuperator will occasionally be subjected to over temperature conditions due to equipment failures, etc. However, certain material properties such as limiting creep stress deteriorate almost exponentially with increasing temperature. Hence, designing a recuperator conservatively by minimizing stresses can avoid the potential for serious recuperator damage in these situations.

combustion air may leak into the waste gas stream. If the process is operating with excess fuel, secondary combustion occurs as the fuel rich waste gases leaving the process combine with this leaking combustion air and burn. Since secondary combustion usually takes place within the recuperator, extremely high metal temperatures can develop. Recuperator deterioration then can proceed quite rapidly via the above listed mechanisms. It should be pointed out that secondary combustion is more of a problem in a system where the combustion air flow for combustion control is metered before the recuperator. In these systems, a recuperator air leak will cause combustion air to short circuit to the waste gas stream after it has been metered but before it reaches the process. This situation can cause the process to become fuel rich and create the necessary conditions for secondary combustion. Combustion air metering on the hot air side of the recuperator is preferred to cold side metering since it eliminates this potential problem.

Today, it is obvious that a recuperator will expand when it is subjected to elevated temperatures and that its design must allow for the thermal expansion. Nevertheless, some early recuperator failures appear to have been caused by excessive stress created by a failure to allow for thermal expansion. In those cases, recuperator lives of a year or less were experienced. More recently, as recuperator designs have evolved and as recuperator lives have been extended, the nature of the failures appears to have shifted away from thermally induced stresses towards thermal fatigue and high temperature gaseous corrosion.

The formation of sigma phase in recuperator alloys appears to play a role in the failure mechanisms. Sigma phase is a brittle intermetallic chromium-iron compound that forms when chromium bearing steels are heated for long times between 540°C (1000°F) and 930°C (1700°F). The following detrimental effects of sigma phase have been identified: (5) (6)

- Since sigma phase has a different composition than the original alloy, internal thermal stresses within the material can result if the sigma phase coefficient of thermal expansion is different than that of the surrounding material. Furthermore, if the temperature of the material is cycled, these thermal stresses will be cyclic and thermal fatigue may result.
- Since sigma phase is brittle, it may facilitate crack propagation.
- Since sigma phase contains large amounts of chromium, depletion of chromium out of the original alloy results and accelerated corrosion then occurs in the chromium depleted areas.

In one case at Inland Steel, the recuperator metal temperatures were limited to values that inhibited the formation of sigma phase - 590°C (1100°F) maximum. The recuperator life in this case was quite good--14 years with only minor repairs. In another case flue gas plus combustion air were the control variables and actual metal temperature was not controlled. In this case, significant deterioration occurred after only a few years of service. A metallurgical examination of the short lived recuperator's alloys indicated the presence of large amounts of sigma phase. Hence, the evidence suggests that the formation of sigma phase was a contributing factor to the difference in recuperator life.

Until the question of the role of sigma phase formation in recuperator failures can be resolved, it is recommended that recuperators be designed and operated conservatively with regard to this potential problem. Suggested approaches include:

- Controlling maximum recuperator metal temperature to inhibit sigma phase formation, if stainless steel type alloys are used.
- Using iron free alloys to avoid forming sigma phase, e.g., Cabot 214, Inconel 601, Hasteloy S.

Controlling the recuperator metal temperature, as suggested above, also will have a beneficial effect on thermal fatigue. Thermal fatigue is the result of a series of plastic deformations caused by repeated thermally induced expansions and contractions. Since metal temperature control reduces the magnitude of these thermally induced expansions and contractions, metal temperature control can reduce thermal fatigue.

It should be pointed out that carbide precipitation has the potential to cause similar types of problems as sigma phase formation. Use of a low carbon alloy appears to alleviate the carbide precipitation problem.

SYSTEM PERSPECTIVE - Recuperation is only one of many methods for saving energy. In designing a recuperated system, the "system" designers should avoid "tunnel vision" and should consider recuperation in conjunction with other energy saving methods. For example, for some processes, such as reheat furnaces, extending the length of the furnace can provide "natural recuperation." This extended furnace length provides more heat transfer surface area for the hot waste gases to transfer heat to the material being heated. This additional surface area and increased heat transfer lowers the waste gas temperature leaving the furnace. Extending the furnace length, therefore, can affect the design parameters of the recuperator. Hence, if a design incorporates both extended furnace length and recuperation, the recuperator size and furnace length have to be optimized jointly. This, of course, requires the designers to take a system perspective.

PRACTICAL REQUIREMENTS

In order for a recuperator to be integrated into a process, the system design also must be compatible with the process. One key area of compatibility is pressure drop. Many combustion processes are designed to use the natural draft of a stack to remove the products of combustion from the process. A recuperator designed for such a process either must be designed within the pressure drop constraints imposed by natural draft or must incorporate an eductor, etc., to overcome these pressure drop restrictions. The geometry of a recuperator also must be compatible with the facility into which it will be integrated. The piping and structural details must be worked out so that the recuperator can be physically integrated into the process. Finally, the necessary recuperator controls and protection systems must be compatible with the process.

As indicated above, a number of factors need to be coordinated in order to install a recuperator into a process. It is desirable to have the option of being able to purchase a recuperator as a complete package - including all of the necessary design coordination for system performance, piping, structural, controls, etc. However, if such a package is offered, it should be flexible enough to allow the brands of supporting equipment preferred by the customer to be substituted into a general design.

MAINTAINABILITY - Ideally, a recuperator would provide long service life and never need maintenance. In use, however, every recuperator requires a certain amount of maintenance. A recuperator installation, therefore, should be designed to facilitate this maintenance. Where necessary, the design should incorporate provisions to isolate the recuperator from the process so that repairs can be made without interrupting the process. The parts of a recuperator that are prone to failure also should be easily accessible or removable to facilitate inspection and maintenance. Finally, the ability to clean deposits off of the heat transfer surfaces should be provided for those processes in which deposits will occur.

ALTERNATIVE ENERGY SAVING TECHNOLOGIES

So far this paper has concentrated on recuperators. As was pointed out, however, recuperation is only one of several methods for saving energy. In general, any device or practice besides recuperation that reduces the fuel input to a combustion process reduces the economic incentive to install recuperators and exerts competitive pressure on recuperators. Some of these competitive heat saving technologies include:

- Items that reduce the heat load
  a. Better furnace insulation.
  b. Hot connecting. (Charging hot material into the furnace from the previous process.)

- Items that reduce waste gas losses
  a. Oxygen enrichment.
  b. Natural recuperation, i.e., extended furnace length.
  c. Regeneration.

Besides the items that reduce the fuel input to the process, other methods can compete with recuperators by virtue of the fact that they recover heat from waste gases. Such methods include waste heat boilers, low temperature Rankine cycles, etc.

Lately, renewed interest has been directed at regeneration. As previously stated, regeneration is an old technology dating back to the first open hearths and blast furnace stoves. Two regenerative beds make up a regenerative system. When one regenerator is being used to heat combustion air, the other is being heated by the hot waste gases from the process. After a period of time, the flows are reversed and the regenerator that was being heated by the waste gases is now used to heat combustion air and vice versa. The switching process continues at periodic intervals. Regenerators in which the regenerator bed consists of a packed bed of refractory offers the following inherent advantages:

- The preheat air temperature can be quite high - within 55C (100F) of the waste gas temperature.
- The refractory bed is inherently a high temperature material.
- If loosely packed, the bed material is free to expand thermally; hence, thermal stresses are low.
- Regenerators of this type are easily equipped so that the bed materials can be removed, cleaned and replaced.

The major disadvantage of regeneration is the additional complexity and cost associated with the flow switching mechanisms.

Obviously, a number of methods compete with recuperators in the energy saving field. Ultimately the best alternative is the one that provides the greatest value in use.

SUMMARY AND CONCLUSIONS

The requirements and factors to consider in the development of heat exchanger equipment for the steel industry have been described and potential savings and applications indicated. At present day natural gas prices, $159 million/year can be achieved in the steel industry by increasing air preheat temperatures by 220C (400F) in reheat furnaces alone.

In order to use energy as effectively as other major world competitors, the steel industry in the U. S. must lead in the utilization of advanced heat transfer equipment technology. To advance this technology, cooperative efforts between equipment and high temperature alloy material suppliers and steel industry users will be required. Hopefully, these cooperative efforts will be enhanced by this conference on high temperature industrial heat exchangers.

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