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An innovative ceramic high temperature plate-fin heat exchanger for EFCC processes

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Abstract

For heat exchanger applications needing extreme operation temperatures such as in the field of power generation or heat recovery a ceramic plate-fin heat exchanger is proposed, based on the "Offset Strip Fin" design. At first the principal selection of the materials and the environmental barrier coating (EBC) needed to protect the substrate from the aggressive flue gases is explained. Then a manufacturing process is described able to incorporate the EBC on all parts having contact to the flue gases. On the basis of a representative biomass fuelled externally fired combined cycle (EFCC) process with an electrical output of 6 MW the thermal design is presented resulting in a counter flow ceramic heat exchanger block of weight 4.0 t and surface area densities of 443 mm^2/mm^3 on the flue gas side and 286 mm^2/mm^3 on the pressurized process gas side. To ensure the thermomechanical integrity investigations of both the steady state operation and the case of an emergency stop were investigated by means of finite element method (FEM). In the case of steady state operation a security factor of 8.5 was achieved. This demonstrates that the occurring stresses in both cases are controllable.

Keywords: Ceramic plate-fin heat exchanger; Heat exchanger design; Externally fired combined cycle; Heat recovery; Manufacturing

1. Introduction

In the last two decades combined cycles have gained high interest as they offer the most efficient way to generate electricity. However, these processes are restricted to the combustion of gas. Coal or biomass can thus not be electrified as the resulting flue gases are loaded with sooth particles and chemically aggressive slag that imperil the thermomechanically highly stressed turbine vanes. Thus externally fired combined cycles (EFCC) have been proposes (see Fig. 1) in that the compressed air is heated by heat exchangers and then directed through the turbine. After expansion the air is used for the combustion in the furnace. The hot flue gases provide both the high temperature heat transferred by appropriate heat exchangers in the gas turbine cycle as well as the low temperature heat for the steam cycle. Critical for the realisation of the EFCC processes is the high temperature heat exchanger as for usual gas turbine classes it has to face temperatures beyond 1100 °C for the long term. This demands for the development of a ceramic heat exchanger. Beside the high temperature it has to face oxidation from the compressed air as well as hot corrosion from the aggressive flue gases. It has to stand steady state and transient thermomechanical loadings (e.g. emergency stops) as well as the typical pressure ratios of modern gas turbines without significant leakage. For the use in power plants it has to reach a lifetime of 10^5 h.

Beside EFCC processes there are other challenging applications for ceramic heat exchangers, e.g. closed gas turbine cycles. In integrated gasification combined cycles (IGCC) the gasified fuels having temperatures of 1350–1600 °C are quenched with cold gas or water down to 900 °C to prevent overheating the facility [1,2]. Solid oxide fuel cells (SOFC) need heat exchangers that can operate at temperatures of 1000 °C and high steam ratios to remove

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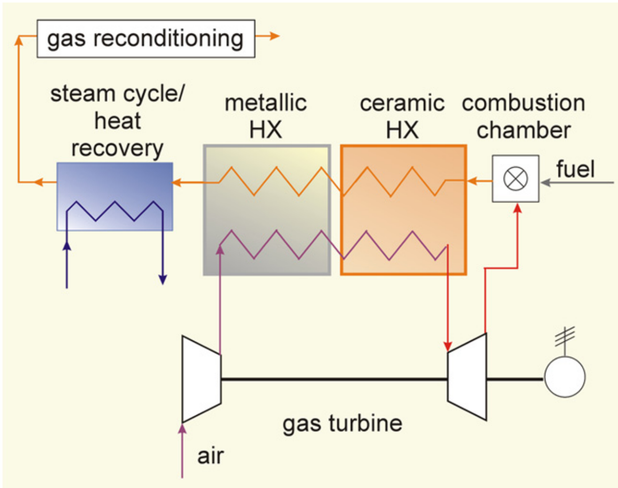

Fig. 1. Schematic representation of an externally fired combined cycle.

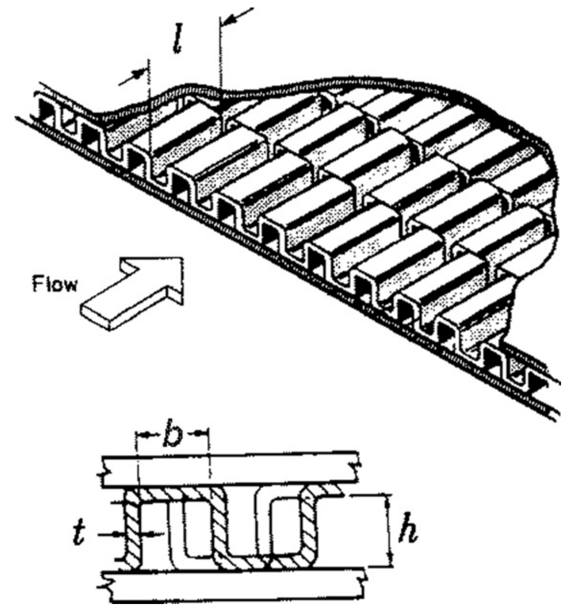

Fig. 2. Basic element of a metallic OSF heat exchanger, the characteristic geometric variables are given.

the reaction heat from the product stream. Beside power generation there is a large potential in the heat recovery of corrosive waste streams at temperatures beyond 1000 °C. For example, only 5% of all aluminium melting furnaces are equipped with waste heat recovery systems [3].

In the literature some concepts for high temperature heat exchangers can be found, mainly on the basis of tube-in-shell or bayonet types [4]. Especially in the decade up to 1984 an intensive research was conducted. These resulted even in a two years field test of a tube-in-shell heat exchanger, composed of SiC tubes partly enhanced by fins, as a waste heat recovery in an aluminium remelt facility. These tests were reported to be highly encouraging [5]. However, the introduction into market failed due to unknown reasons. A tube-in-shell heat exchanger designed for the pressurized pulverised coal combustion combined cycle (PPCCCC) was presented by Maier and Himmelstein [6]. This heat exchanger consists of SiSiC tubes that were fixed on the upper end to the tubesheet, while being able to slip through the other tubesheet. Sealing was achieved by using Al_2O_3-fibre materials. However, this sealing cannot be expected to be sufficient for an EFCC-process that is operated in contrast to the PFCCCC-process at large pressure differences of 1.1–1.9 MPa. An example of a bayonet heat exchanger tube capable to fulfil most of the above mentioned requirements was given by Schmidt et al. [7], who used a ceramic matrix composite to ensure the thermomechanical stability. An environmental barrier coating (EBC) based on a SiC–B_4C–SiC-cordierite multilayer system was used to ensure the resistance against hot corrosion. However, the materials selection and production sequence (ceramic matrix composite coated with three materials by different techniques) is quite expensive and therefore not suitable for large industrial applications.

In the presented work a new type of ceramic heat exchanger is proposed based on the offset strip fin (OSF-) design. This is a plate-fin design, in that the fins are interrupted and arranged in rows. Each subsequent row is offset by a certain part of the fin spacing. This arrangement leads to a periodic restart of the boundary layer resulting in a substantial heat transfer enhancement [8]. Thus this configuration is regarded as giving the best performance (except for winglet designs) [9]. In the case of metallic heat exchangers an OSF structure can be easily realised by welding or brazing folded bands on the base plates (see Fig. 2).

When transferring this design on ceramic high temperature heat exchangers that may be used in the mentioned applications, some important issues have to be considered. The materials have to stand the above described, harsh conditions for the demanded lifetime of 10^5 h. It was found that these demands can only be fulfilled with a protection against corrosion. On the basis of the chosen materials a manufacturing process has to be developed that is able to incorporate the EBC on all sections that are loaded with flue gases during operation of the heat exchanger. Keeping the constraints of materials and production in mind the thermal and thermomechanical design can be done. The first was in this case conducted by using empirical correlations drawn from the literature, while the latter was developed by means of finite element method (FEM). In the subsequent sections these items are described resulting in the complete layout of both flue and process gas plates that are the basic elements of this type of ceramic heat exchanger.

2. Materials selection

As already written the demands of the EFCC process cannot be fulfilled by only one material. Thus a separation of function had to be applied by using an environmental