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Heat transfer, pressure drop and structural analysis of a finned plate ceramic heat exchanger

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ABSTRACT

High temperature heat exchangers (HTHE) constructed with ceramics can achieve higher temperatures of operation. Resistance to oxidation is the great advantage of using ceramics for this application. This paper presents experimental characterization of one ceramic heat exchanger composed of finned plates operating at temperatures as high as 800 °C and Reynolds number between 170 and 2000. The heat exchanger operates in counter-flow with air in both sides. The plates were constructed using alumina (Al_2O_3) with the Gelcasting technique. Thermal performance was obtained in the form of Colburn and friction factors as a function of Reynolds number. The heat exchanger effectiveness varied between 0.620 and 0.901. Progressively higher temperature was imposed to the heat exchanger prototype to cause structural failure. In addition, the design and structural integrity assessments were carried out using refined finite element computations based on real experiments regarding fracture resistance of the employed ceramic. Thermal performance of the ceramic heat exchanger is adequate and predictable using CFD simulations, but guarantee structural integrity remains challenging.

1. Introduction

High temperature heat exchangers (HTHE) enable the increase in performance of a number of industrial processes and heat engines. In general, the higher the temperature one HTHE can withstand, the greater the system performance improvements achieved. Also, a number of chemical reactions that require high temperatures could be performed in ceramic heat exchangers such as the sulfur trioxide decomposition [1] and production of syngas for Fischer-Tropsch fuels [2].

The externally fired gas turbine (EFGT) [3] is one thermodynamic cycle that could be implemented using this kind of heat exchangers [4], enabling also the burning of biomass in gas turbines [5–7]. The EFGT cycle has been implemented experimentally [8,9] using metallic HTHE, demonstrating the feasibility of the cycle, but the use of metallic heat exchangers introduced a serious limitation: the turbine inlet temperature (TIT) must be maintained lower than 750 °C, a metallic material limitation even if Nickel-based superalloys are employed.

As pointed by Ref. [10], the use of ceramics for the heat exchanger construction should be considered as an option to settle this temperature limitation. An analysis of the TIT influence over the efficiency of EFGT cycles is presented in Ref. [11], showing that electric efficiency and power output is higher for higher TIT. Using simulations and a detailed model for the ceramic heat exchanger, including pressure drop effects [12], illustrated that EFGT cycles could benefit from the use of ceramic heat exchangers.

The use of plate and fin heat exchangers configuration for the construction of ceramic HTHE [13–15] is feasible and provides high heat transfer area per volume of the heat exchanger. The thermal performance and pressure drop of this configuration could be predicted using the standard approach already used for compact heat exchangers [16] and Colburn and friction factor correlations can be obtained experimentally [15] for each geometry. The use of these correlations is not limited to the design of ceramic HTHE, but also to simulations of the systems in which the heat exchanger is introduced [17].

The development of the Colburn and friction factor correlations in a convenient format, as introduced in Ref. [18], using CFD simulations including laminar, transition and fully turbulent regimes is presented in Ref. [19]. The inclusion of geometrical parameters of the HTHE on the correlations is presented in Ref. [20].

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Technology needed for the construction of plate and fin ceramic heat exchangers is not established yet. Mechanical integrity of ceramics is an area of intense development [21,22] Some successful attempts can be found in literature [14,23,24], that considered the use of ceramic heat exchangers for different applications. However, some aspects of thermal, fluid and structural responses are considered as open-issues.

The main objective of this work is the validation of the Colburn and friction factor correlations obtained using CFD simulations with experimental data. Also, develop a better understanding of the process which lead to structural failure of the HTHE reported in Ref. [15].

The present work extends [15] by constructing a new ceramic HTHE prototype using alumina (Al_2O_3) and testing it in a greater Reynolds number range. Previously, Reynolds range was limited to 500 and is increased to 2000 with new experiments. The heat transfer and pressure drop in a plate and fin ceramic heat exchanger is evaluated experimentally. The disagreement of experimental results with numerical results for the friction factor observed in Ref. [15] is attenuated by using new pressure transducers with adequate full scale, another improvement of this work.

Details related to the construction of the heat exchanger are discussed, including its structural integrity assessment and failure prediction based on the mechanical strength of alumina obtained by mechanical tests. This structural analysis was not present in Ref. [15] and is the main novelty of present work. The experimental set up to evaluate the performance of the heat exchanger is fully described. Results are presented, compared to CFD simulations and discussed. A structural integrity assessment is carefully conducted during each test for the determination of the conditions that lead to the structural failure. In addition, refined finite element computations using the Modified Mohr-Coulomb criteria allowed the failure prediction of the heat exchanger. The thermal results, combined to structural design and failure predictions, provide additional understanding on the design and manufacture of ceramic HTHEs.

2. Ceramic heat exchanger construction

A ceramic heat exchanger has been constructed composed of eight finned plates, being one of them used only as cover, as shown in Fig. 1. The geometry of the finned space was carefully designed using CFD simulations, already described in previous work [12,19]. The geometrical design of the heat exchanger is conducted in order to obtain effectiveness equal to 0.70 for Reynolds number 1000.

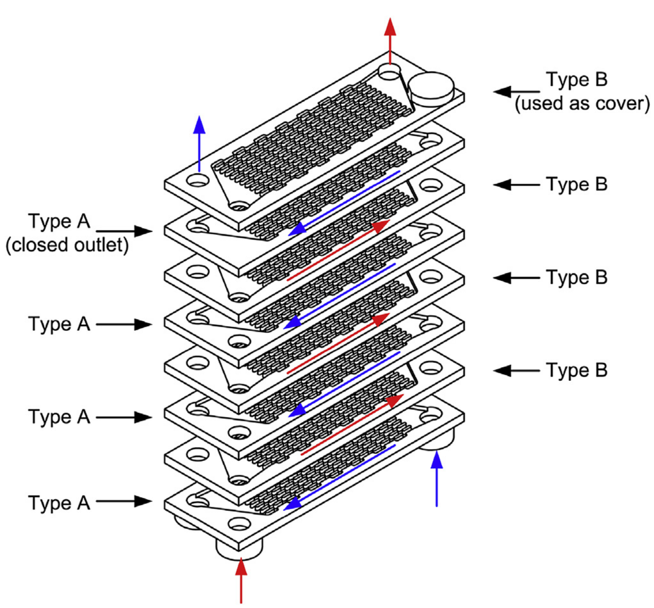

Fig. 1. High temperature heat exchanger constructed using finned ceramic plates.

The manufacture of the ceramic plates was carried out using the Gelcasting technique [25] due to its complex geometry. This technique requires a mold to define the geometry of the plate.

In Fig. 2, two different molds are shown: the first one was used to test the manufacturing process with smaller plates; the second one is the mold used for the manufacture of the heat exchanger. Both molds are covered with a polytetrafluoroethylene layer to ease the unmold process of green plates. The laterals of the second mold can be disassembled, also with the purpose to ease the unmold process. The second mold allows constructing plates of type A and B (Fig. 1) changing the central part that defines the fin geometry.

The plates were constructed using alumina (Al_2O_3). The Alumina properties used for the design of the heat exchanger took into account the porosity resulting of the fabrication process. Models obtained by Ref. [26] were applied to the dense properties available in literature [27]. Tests with the first mold suggested that careful drying of green plates is critical in order to minimize warping and cracks. Besides, significant improvements were achieved using osmotic drying [28]. In the present case, one plain base for the sintering process was essential to avoid warping of the plates. All the plates were sintered separatelly, before final assembly of the heat exchanger.

The joining of the plates in the arrangement shown in Fig. 1 was conducted using ceramic cement. After drying of ceramic cement, a final sintering is conducted. Despite the heat exchanger formed with this joining is not capable of withstanding high pressure between the plates, the authors did not observe any apparent air leakage between the plates during the experiments. Of course, this joining technique imposes serious limitations for real applications and a better one should be developed in order to use plate and fin ceramic heat exchangers with EFGT. On the other hand, it does not affect the objectives of the present work.

Kee et al. [14] applied a strategy of sintering the green plates assembled as the final geometry of the heat exchanger which resulted in a single solid. Despite the success presented by Ref. [14], it is noteworthy that the ceramic heat exchanger manufactured had small dimensions (50 mm × 100 mm x 28 mm) and further research must be done to apply this strategy on larger ceramic heat exchangers.

The external dimensions of each plate and the fin arrangement are shown in Fig. 3. Each plate presents 6 mm of wall thickness and the fins are 6 mm high resulting in a total thickness of 12 mm for each plate. Once the green plates are dry and sintered the

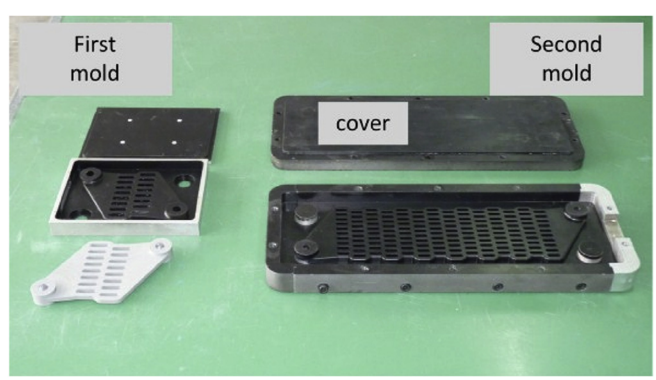

Fig. 2. Left: First mold used for exploratory manufacturing experiences, Right: second mold used for the construction of the heat exchanger.

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