Conceptual design and performance evaluation of an innovative high temperature ceramic heat exchanger

S A Zavattoni, L Cornolti, E Arrivabeni, R Puragliesi, A Ortona and M C Barbato
Department of Innovative Technologies, SUPSI, 6962 Lugano-Viganello, Switzerland

E-mail: simone.zavattoni@supsi.ch

Abstract. The development of an innovative and highly efficient heat exchanger (HE) solution for gas-gas heat recovery is one of the major objectives of the HYDROSOL-beyond project which aims at enhancing the process efficiency for producing H₂ from water dissociation with concentrated sunlight. Because of the very high temperature level of the process (up to 1’400°C), an innovative ceramic HE was proposed with an integrated lattice structure, as secondary surface, to maximize the heat transfer. To assist the design of the HE, a multiscale approach was adopted: a 1D model based on global correlations was developed and a 3D computational fluid dynamics model of the secondary surfaces were generated. The former was applied to assess the performance of the entire HE; while, the latter was exploited to study in detail the thermo-fluid dynamics behavior of a HE core element and to provide the global correlations to be integrated into the 1D model. The effect of the number of lattice layers, located into each channel, on the HE effectiveness was evaluated showing that reducing the height of the secondary structure allows to improve the HE effectiveness from 72% up to 94%.

1. Introduction
To successfully proceed along the energy transition path from a fossil fuel based economy to a clean energy based economy, solar energy will play a paramount role. However, to reliably exploit this energy source, technical challenges, due to its intrinsic intermittent availability, have to be tackled. A possible solution could be the conversion of solar energy into an energy carrier such as hydrogen (H₂). To this purpose, the EU funded HYDROSOL-beyond project [1], the last of a twenty-years HYDROSOL projects history, is an ambitious scientific endeavor which aims at addressing the major challenges, identified during the previous projects, to further boost the process efficiency of H₂ production from water dissociation through reversible reduction-oxidation (redox) thermochemical reactions and concentrated solar energy [2]. In this process, the highest temperature level into the receiver/reactor, of about 1’400°C, is achieved during the metal oxide reduction step. For a proper execution of this step, a large amount of nitrogen (N₂) gas flow is required to purge the reactor. Since the N₂ gas flow leaving the receiver is at very high temperature, recovering as much as possible of this amount of thermal energy will remarkably increase the performance of the whole process. For this reason, one of the major objectives of HYDROSOL-beyond project is the design and development of an innovative and highly efficient solution for gas-gas heat recovery system operating at very high temperature levels (> 1’000°C). The present study aims at showing the developed strategy to preliminarily design this component by evaluating its performance for different geometrical configurations and materials.
2. Gas-gas heat exchanger design

Gas-gas heat exchangers (HE) are devices devoted to transfer heat between two or more gaseous fluids at different temperatures. According to literature, plate-fin HE is the common solution for gas-gas applications with very high effectiveness (up to 0.95) [3]. As schematically represented in Figure 1, plate-fin HEs are constituted by a stack of several layers, separated by parting sheets, through which the two gaseous streams flow alternatively in counter- or cross-flow arrangements. An additional structure, called fin or secondary surface, is integrated between the parting sheets with the twofold aim of enhancing the heat transfer and providing mechanical support to the HE structure. The plate-fin HE was selected as starting point for the design of the HE to be implemented into the HYDROSOL process which requires a system with high operating temperature, high effectiveness and compact design. Since operating temperatures will be well above 1'000°C, ceramics materials are the only suitable candidates for the HE body. Furthermore, to maximize the heat transfer performance, the design included lattice structures as secondary surface. Therefore, the whole HE will be realized in Zirconium dioxide (ZrO$_2$) with integrated lattice structure based upon tetrakaidecahedron (Kelvin) cells.

![Figure 1. Plate-fin HE schematic and example of common secondary structures [3].](image)

3. Numerical models development

The conceptual HE core design was performed by combining the information acquired from two different numerical tools: (i) a 1D numerical model, based on semi-empirical correlations designed to evaluate the global HE effectiveness; and (ii) a 3D computational fluid dynamics (CFD) approach suitable to obtain detailed information on the fluid flow and heat transfer behaviour. The coupling between these tools was realized via specific correlations implemented into the 1D model and derived through several 3D CFD simulations campaigns varying relevant geometric and operating parameters.

3.1. 1D model

The HE can be schematized as a stack of pairs of parallel channels in which hot and cold fluid streams flow alternatively in counter-flow arrangement (Figure 1). The 1D model considers one of these pairs only, assuming that all of them behave in the same way. This element is divided into three subsystems: the hot and cold fluid channels and the solid parting plate between them. For each of these subsystems, the energy balance equation is solved with the addition of mass and momentum equations for the fluid phase. These equations are discretized along the axis of the HE. The solid plate is modeled with a quasi-2D approach: the temperature profile inside the solid is assumed to be a polygonal chain formed by two segments (see Figure 2) with a sudden change of slope in the middle point of the cell due to the longitudinal heat flow ($Q_L$) imbalance, which is supposed to be concentrated in this point. This causes jump of the local transversal heat flux value ($Q_T$) and therefore a variation of the temperature profile slope. The two strain lines (blue and red) in Figure 2 represent the assumed temperature profiles along the transversal direction. $Q_{T,HW}$ is the heat flux entering the wall from the hot gas side, $Q_{T,WC}$ is the heat exiting the wall towards the cold gas side. When the difference between $Q_{L,1}$ and $Q_{L,2}$, which in steady state is equal to the difference between $Q_{T,HW}$ and $Q_{T,WC}$, is not zero, the slope of the temperature profile between $T_{W,H}$ and $T_{W,C}$ is different from the one between $T_{W}$ and $T_{W,C}$. In this way, the model includes both the effects of transverse and axial heat fluxes, where the latter can play a significant role for high efficiency HE.
Figure 2. Schematic of the wall which separates the channels: three consecutive computational cells are represented together with the exchange of heat fluxes of the central cell.

Figure 3a shows the influence of solid material thermal conductivity on the HE effectiveness: the HE effectiveness function has a maximum due to the tradeoff between the transverse resistance, which decreases with increasing conductivity, and the heat flux along the axis, which increases with increasing conductivity (black line). Without the latter contribution, the effectiveness increases with thermal conductivity only (red line). The effectiveness reduction can be explained through Figure 3b which shows that it’s linked to the shape of the temperature profiles close to the inlets of the hot and cold sides.

Figure 3. a) HE effectiveness as function of the solid thermal conductivity for a fixed geometry. b) Temperature profiles along the axis of the HE in case of solid material with high thermal conductivity.

The secondary structure geometry is also accounted for through its specific heat transfer area, porosity, and fin efficiency. Pressure drop and convection coefficients are computed through correlations obtained from experimental data or appropriate CFD simulations. $N_2$ properties are modeled as a function of temperature and pressure through standard gas equation of state and gas kinetic theory expressions [4]. The 1D model is exploited to extend the CFD simulations results to the entire HE, and to find, for the assigned target effectiveness, the dimensions of the HE which minimize its volume and number of plates (linked to cost and thermal inertia reduction).

3.2. 3D CFD model

The CFD model, developed with Fluent code from ANSYS, solves continuity, momentum and energy conservation equations. Based upon the operative $N_2$ flow rates range, laminar flow regime can be considered for all the simulations. Thermal radiation heat transfer into the computational domain is also accounted for by the surface-to-surface (S2S) radiation method. Temperature dependent physical properties were considered for both ZrO$_2$ and $N_2$. The latter, was modeled as an ideal gas.

The 3D computational domain, considered for the analysis, and depicted in the r.h.s. of figure 4, is constituted by two parting sheets separated by a 19.35 mm high and 19 mm long lattice structure containing a total of 27 tetrakaidecahedron cells of 6 mm equivalent diameter. Since a single channel only was considered, constant temperature boundary conditions were set on the parting sheets to replicate the presence of the lower temperature countercurrent $N_2$ flow. Grid-independent results were obtained with about 5 million cells. Spatial discretization of the transport equations were performed with a second order accurate upwind scheme. Convergence was considered to have been achieved when mass and momentum residuals were below $10^{-5}$ and energy residual was below $10^{-9}$. 
4. CFD simulations campaign – Effect of channels height on the HE performance

The aforementioned 3D CFD model was extensively applied to evaluate the thermo-fluid dynamics behaviour of the HE representative core element subjected to various boundary conditions and/or topological variations. As an example, in this CFD simulations campaign, the effect of the number of lattice layers, constituting the secondary structure, on the HE performance was evaluated. In detail, starting from the reference condition depicted in figure 5a, the number of layers was reduced down to 2 (figure 5b) and 1 (figure 5c). The equivalent cells diameter was kept unchanged as well as all the boundary conditions (BC) considered. Concerning the latter, constant temperature BCs, of 1'440 K and 1'473 K, were applied on the parting sheets and the inflow stream respectively. The same N\textsubscript{2} mass flow rate was considered through the whole HE, assuming a constant N\textsubscript{2} inlet velocity BC, for all these three cases. The CFD simulations results allowed to observe a monotonic increase of the HE core effectiveness. In particular, a 0.72 HE effectiveness was obtained for the reference lattice geometry with 3 layers followed by 0.84 and 0.94 HE core effectiveness in the case of 2 layers and 1 layer respectively.

5. Summary and conclusions

An innovative ceramic HE was preliminarily conceptualized with the aim of improving the overall efficiency of the HYDROSOL process, for exploiting water dissociation for H\textsubscript{2} production with concentrated sunlight, through the recovery of heat from the high-temperature N\textsubscript{2} flow leaving the receiver/reactor during the process. To assist the HE preliminary design phase, two numerical models have been developed: a 1D model based on semi-empirical correlations to evaluate the performance of the entire HE core and a 3D CFD model to perform detailed thermo-fluid dynamics analysis of the HE under various topological and/or operative conditions. The results of a CFD simulations campaign, aimed at evaluating the effect of the number of lattice layers in each channel on the HE effectiveness, was reported showing that reducing the height of the secondary structure has a beneficial effect on the HE performance with the effectiveness moving from 0.72 up to 0.94 in the case of the reference 3 layers configuration and the 1 layer respectively.

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