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Design of a Condensing Heat Recovery Integrated with an Electrostatic Precipitator for Wood Heaters

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Abstract. High emission of particulate matter from fixed sources of biomass combustion and the effects on the health of the population have driven the implementation of public policies for changes in the energy matrix and a technological replacement in Chile. Due to this, a prototype of a condensing heat exchanger is developed integrating an electrostatic precipitator, seeking to enhance the positive effects of these technologies in a single and relatively compact device. The state of the art shows similar developments, but with high levels of complexity in construction, as a shell and tube heat exchanger, that is why the concept of a thermocannon was optimized to condense the moisture present in the fumes and reduce smoke emissions through an electric field. It is expected that using an electrostatic precipitator, up to 90% of particulate matter emissions will be captured, and thermal efficiencies of an additional 9%. For its design, heat transfer and thermodynamics models were used and validated through CFD modeling.

Keywords: Domestic hot water · Condensing heat exchanger · Electrostatic precipitator · Biomass

1 Introduction

In Chile, biomass is the second primary energy source after oil corresponding to 23% of the total energy matrix of the country [1]. However, it is responsible for air quality problems in the main populated areas of the country contributing to 81.5% of the particulate matter (PM) emissions [2], mainly from residential wood combustion.

More than half of the Chilean population is currently exposed to concentrations of fine particulate matter or $PM_{2.5}$ (particulate matter with aerodynamic diameter ≤ 2.5 μm) above the annual limit being one of the highest levels among OECD countries [3]. Air pollution is the most important environmental problem in Chile [4], since it has negative effects on human health from exposure to particulate matter are associated with cardiovascular and pulmonary mortality and morbidity events.

Proposed improvements for wood heater included catalyst filters with PM reduction efficiency near 60% [5] or living filters that reach efficiencies of 95% [6]. Some

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manufacturers incorporate post-combustion chambers with secondary air injection that reduce PM emissions and other pollutants by up to 90% [7]. In addition, electrostatic precipitators are available to adapt to the chimney, with PM reduction efficiency up to 90% [8] or installed in the combustion chamber with 44% reduction efficiency [9].

To improve the thermal efficiency of wood heaters, water heating thermos (thermocannon or thermosyphon) add-on are available with capacities from 70 to 110 L. A second combustion chamber also favors energy efficiency by providing additional convective heat to the radiation emitted by a conventional stove, saving up to 50% in fuel [7]. Proposed solutions for wood heaters consisting of compact shell and tube condensing heat exchangers [10–12] may increase thermal efficiency up to 33% and can incorporate a MP reduction device.

This study optimizes the thermocannon concept by improving heat transfer and integrating an electrostatic precipitator to reduce PM emissions. It is expected that, as in [12], a synergy between both devices would reduce PM emissions by 85% and increase thermal efficiency by 20%.

2 Methodology

A thermodynamic model was developed for the numerical simulation of a modified thermocannon prototype. The first step considers the combustion and heat transfer processes in the heater. The second step includes the heat exchange between the gases and the water in the thermocannon, and the capture of PM and the condensation of the fumes. The last step comprises a 3D simulation, through the finite volume method using the Ansys Fluent CFD tools to evaluate aspects related to the fluid dynamics of heat transfer from the combustion gases to help through the design of an optimized solution, which will be further implemented and validated in an experimental environment.

2.1 Combustion

The biomass combustion step was modeled from the chemical reaction Eq. (1) to characterize the products present in the combustion fumes. In the reactants, the fuel of composition CHxOyNz was considered, including humidity (n_{wb}), combustion air (n_{wa}), excess of air (e) and the stoichiometric oxygen fraction ($XO_{2\,est}$).

$$CH_xO_yN_z + (n_{wb} + n_{wa})H_2O + X_{O_2est}(1+e)\left(O_2 + \frac{79}{21}N_2\right) \rightarrow b_1H_2 + b_2CO + b_3CO_2 + b_4H_2O + b_5N_2 + b_6O_2 \quad (1)$$

Once the composition of the combustion products (b_i) is known, the temperature of the fumes (T_h) entering the heat exchanger is obtained using Eq. (2) to determine the yield (η_{fumes}) by the indirect method or smoke losses (Q_{fumes}) and by incomplete combustion of carbon monoxide (Q_{CO}) based on its lower heating value (LHV_{CO}), where Q_{comb} represents the energy contributed by the fuel based on its lower heating value (LHV_{comb}). The enthalpy of the gases exiting the heater was the same at the entrance of the heat exchanger with a reference temperature (T_r) of 25 °C. The above is resolved iteratively by setting a thermal performance for the heater, considering 80% [13].

$$\eta_{fumes} = 1 - \frac{Q_{fumes} + Q_{CO}}{Q_{comb}} \quad (2)$$

$$Q_{fumes} = \sum\nolimits_{i=1}^{6} b_i[h_i(T_h) - h_i(T_r)] \quad (3)$$

$$Q_{comb} = LHV_{comb} \cdot n_{comb} \quad (4)$$

$$Q_{CO} = LHV_{CO} \cdot b_2 \quad (5)$$

Then, considering a perfect gas mixture, it is possible to calculate the dewpoint temperature (T_{dewp}) by determining the partial pressure of water in the gas flow.

2.2 Heat Exchanger Design

The design was based on a concentric tube attached to the exhaust of a wood stove in which water is heated through a two-stage heat exchanger (Fig. 1) to increase the residence time and turbulence of the fumes. In the second stage, an electrode was integrated based on a commercial 15 kV device. Preliminary dimensions were height 1.35 m, effective length 1.30 m and width 0.46 m (18″ largest diameter). Figure 1 shows improvements added to the original model including a divider plate moved towards the first stage and added turbulence generators to increase the residence time of the fumes.

Heat transfer was calculated using correlations included in the Engineering Equation Solver software, described in [14]. The calculation of the global heat transfer coefficient was simplified since the film thickness in case of condensation does not influence more than 3%, as well as the wall thickness [15]. With the preliminary dimensioning and characterized fume flows, the prototype was modeled in CFD for the initial design.

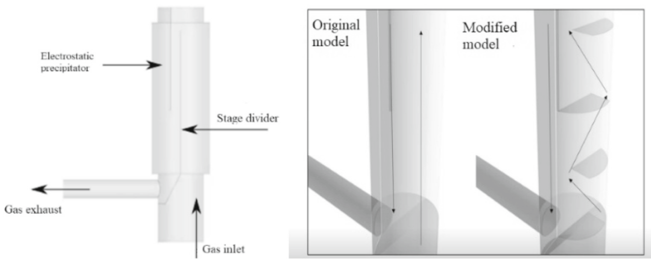

Fig. 1. Original design and improvement proposal.

The behavior of the flow of gases in the heat exchanger used the Cold Flow scope excluding the chemical interactions between the particles and considering only the physical interactions between them and the surrounding geometry [16]. The k-ω SST turbulence model [17, 18] was selected with mesh amounts up to 3.7 million cells.

3 Results

Input parameters for the simulation of the wood combustion and heat exchanger model are shown in Table 1.

Table 1. Input variables for computational study in CFD using the Cold Flow scope.

Variable	Water	Gases	
		Stage 1	Stage 2
Inlet temperature [C]	14.9	183.0	138.6
Outlet temperature [C]	18.6	138.6	107.0
Dew point [C]		51.29	
Flow [kg/s]	0.04167	0.00745	
Convective coefficient [W/m^2-K]	114.7	2.767	2.598
Reynolds number	71	1664	1808
Density [kg/m^3]	1000	0.850	
Combustion gas composition	CO [%]	0.160	
	CO_2 [%]	10.780	
	N_2 [%]	68.610	
	O_2 [%]	7.287	
	H_2O [%]	13.160	

Figure 2 shows the behavior of the gas flow through the representation of the current lines. It is appreciated that the turbulence generators increase the speed of the flow and the intensity of turbulence by 18% in the first stage.

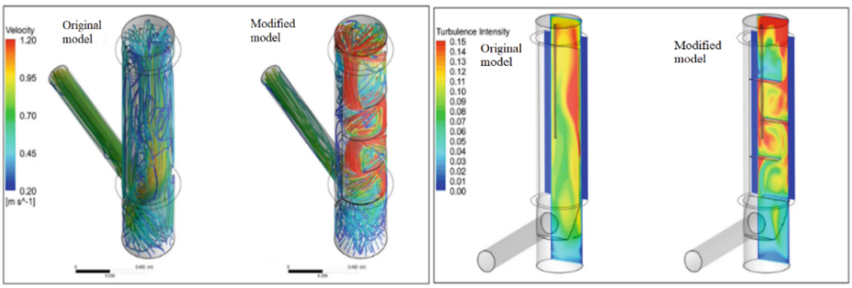

Fig. 2. Streamlines for the models (left) and turbulence intensity section plane, stage 1 (right)

Figure 3 shows the temperature profiles in a section plane of the first stage of the heat exchanger evidencing the improvement in the optimized design. 1.

The new model allows a 15 °C reduction in the temperature of the gases exiting the exchanger (from 82 to 67 °C). The dewpoint temperature was approximately 60 °C and the pressure drop was 12 Pa. The latter occurs due to the low outlet temperature and throttling by the modification in stage Based on the results, it was considered necessary to add a fan at the chimney outlet to push the fumes during the ignition phase.

Concerning the installation of the electrode that delivers the electric charge to the particles in the fumes, the results suggested adequate conditions for its operation with phase velocities of 0.6 m/s [19, 20] and temperature below 90 °C [21, 22]. Regarding energy recovery efficiency, the temperature of the combustion gases was reduced from 183 °C to 67 °C, equivalent to 0.96 [kW] transferred to the water. In theoretical terms and pending the experimental validation of the CFD model, the heat exchanger may increase the overall efficiency by 9.9%.

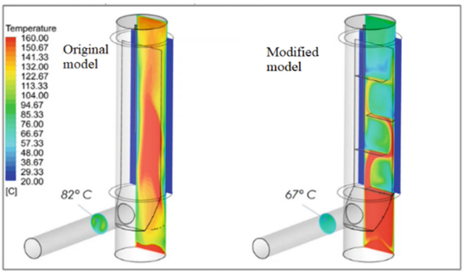

Fig. 3. Temperature profile, section plane (stage 1)

4 Conclusions

A two-stage thermocannon design was proposed for heat recovery and PM emission reduction for wood stoves and heaters. The presence of condensate is still not significant due to the lower heat exchange in the second stage, which is restricted to incorporate modifications due to the presence of an electrostatic precipitator that requires a free cross section of at least 5″ in diameter. Recent literature indicates that the integration of both devices allows to enhance its overall performance, which is expected to be validated in a laboratory environment. Although the alternatives proposed in the literature have higher thermal efficiencies, they are solutions of high cost and complexity. Therefore, the proposed design is adequate for current needs in Chile.

One matter to be resolved during the design process corresponds to the maintenance of the heat exchanger, since the electrostatic precipitator will deposit particulate material on the walls of the device, transforming the surface into a conductive material over time, with possible short-term problems. Due to the complexity of the design, especially stage 1, a configuration that allows easy access to both stages for proper wall and electrode maintenance is in the iteration process, without compromising the efficiency and performance of the device.

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