Heat Exchanger Optimization for Domestic Fireplaces Via Computational Fluid Dynamics Simulations

R. Dul [1], A.B. Palotas [2], K.Jarmai [3]

[1] CFD Engineering Hungary Ltd. 2113 Erdokertes, 15th Palya Str. Hungary

[2] University of Miskolc Department of Combustion Technology, 3515 Miskolc-Egyetemváros, Hungary

[3]. University of Miskolc Department of Materials Handling and Logistics, 3515 Miskolc-Egyetemváros, Hungary

Keywords: fireplace, heat exchanger, computational fluid dynamics, simulation, optimization

Abstract. In this paper authors describe the methodology used for finding an optimized solution for a welded steel heat exchanger connected to a domestic fireplace. Several different versions including crossflow, spiral flow with parallel-flow and counter-current flow directions in terms of main airflow and their combinations were examined during the product development stage, each of them analyzed with computational fluid dynamics (CFD) software. In the CFD simulations several important operating parameters were checked like temperature reduction on the flue gas side, temperature increase on the air side and pressure loss in both flows. Our aim was to find an optimized solution of construction providing the maximum of temperature reduction of flue gas and the minimum of pressure loss in both flows. The results of CFD simulations for the main geometry versions and the methodology of finding an optimized solution in terms of the above aim functions are presented here.

Introduction and geometry of the heat exchangers

The aim of using a heat exchanger on top of a fireplace is to utilize the heat of the flue gas that would leave the system anyway to preheat the air necessary for burning and this way to increase the efficiency of the fireplace and also to help improving air and wood gas mixing in the fire chamber, it is especially true for the secondary air and wood gas mixing.

In the development concept there were three major designs we started to work on. These were the cross-flow tubular (Fig. 1.), spiral plate (Fig. 2.) and spiral tube (Fig. 3.) constructions.

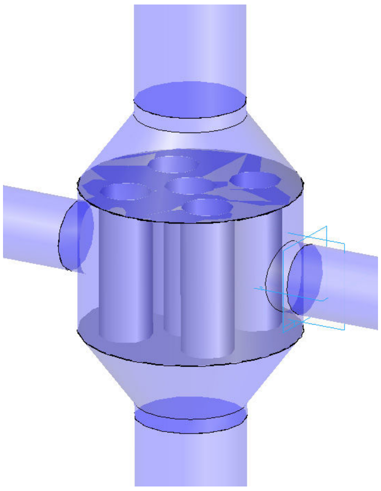

Fig. 1. Cross-flow tubular construction

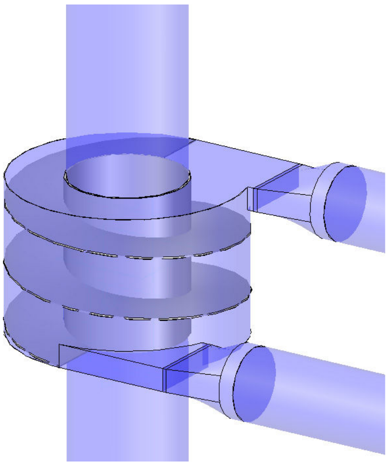

Fig. 2. Spiral plate construction

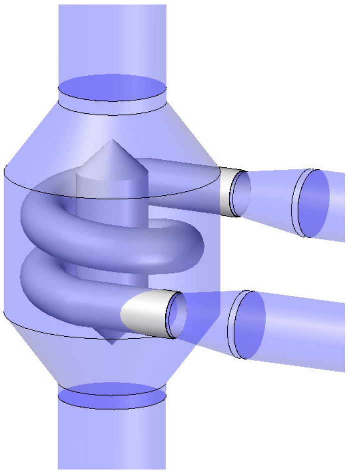

Fig. 3. Spiral tube construction

The first computational fluid dynamics (CFD) simulations were carried out on a fixed sized heat exchanger drum (in which we put the tubular or spiral heat exchanger insert) to examine the efficiency of the major design variations in order to see which construction was the best for further development. In each case the flue gas pipe had a diameter of 150 mm, the air inlet had a diameter of 95 mm, the outside diameter of the heat exchanger drum was 300 mm, the height of the insert was 200 mm, the material thickness of steel sheets was 1 mm. In every version the flue gas flew in vertical direction, the air flew in horizontal direction.

For each major design we created some sub-versions and completed the CFD simulations for all of them. The sub-versions of cross-flow heat exchanger insert can be seen on the following figures.

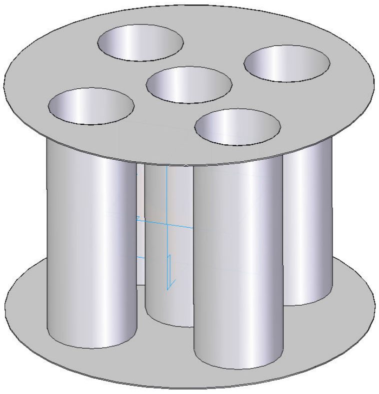

Fig. 4.a. Insert with 5 pieces of Ø70 mm tubes

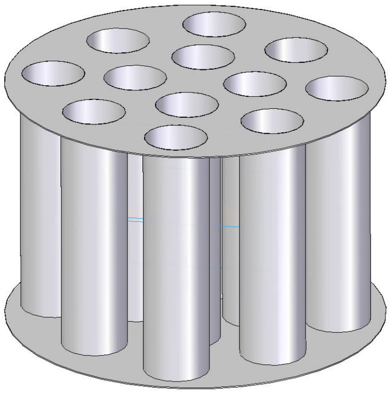

Fig. 4.b. Insert with 12 pieces of Ø50 mm tubes

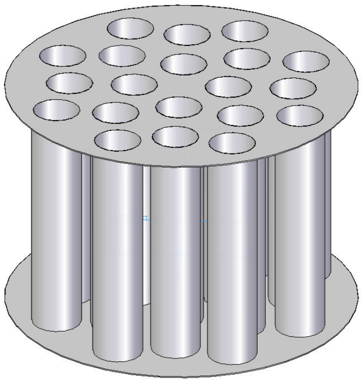

Fig. 4.c. Insert with 20 pieces of Ø40 mm tubes

Some of the sub-versions of spiral plate heat exchanger insert can be seen on the following figures.

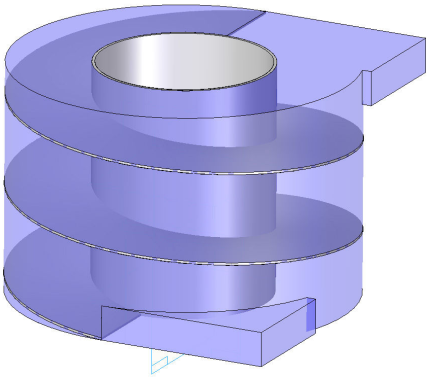

Fig.5.a Spiral plate insert with 2.5 turns

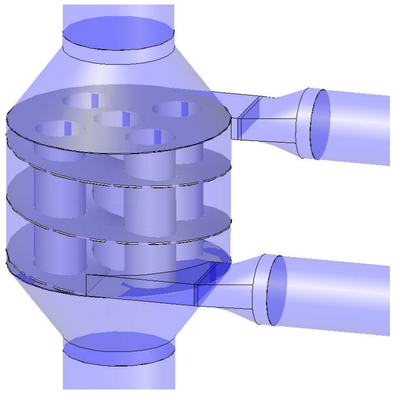

Fig.5.b Spiral plate insert with 2.5 turns and 5 pieces of Ø70 mm tubes

Boundary conditions of the simulations

The boundary conditions were always the same for all geometry versions in order to make each design comparable in terms of performance.

The boundary conditions on the flue gas side consisted of the mass flow of the flue gas, which was m_{fgs}=8.4 g/s and the temperature of the flue gas at the inlet was also fixed at T_{fgs}=300°C which were coming from standardized measurements of a fireplace with 8 kW heat performance. The outlet boundary condition on the flue gas side was set as p=0 Pa static pressure which meant that the end of the flue gas pipe is open to the atmosphere.

On the fresh air side the boundary conditions consisted of the mass flow of air m_{air}=7.64 g/s which is the amount of air that is needed to produce m_{fgs}=8.4 g/s flue gas mass flow [1], its temperature was T_{air}=0°C, since this type of fireplace receives the air directly from the environment.

Fininte element mesh and material properties

For the CFD simulations commercial software called CFdesign was used, the software was developed by Blue Ridge Numerics Inc. (USA). The algorithm was based on a finite element mesh that was created from tetrahedral elements based on the three dimensional CAD geometry. Figure 6. shows the finite element mesh of the cross-flow tubular heat exchanger.

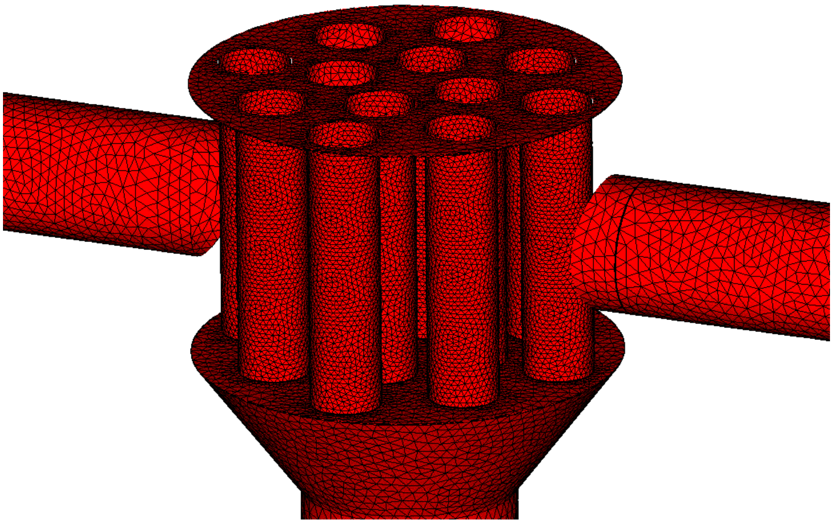

Fig.6 Tetrahedral mesh of the cross-flow heat exchanger

In our simulation the material properties of gases were the functions of temperature. This implementation was very important because the flow and temperature field inside the heat exchanger was determined by natural convection because of the small flow velocities. Table 1. and Table 2. show the material properties of flue gas and air, respectively.

Table 1. Properties of flue gas created by burning oak with 12% water content

Property	Temperature	Value
Conductivity	0	0.0243 W/mK
	1927	0.1446 W/mK
Density	0	1.2925 kg/m^3
	1927	0.1604 kg/m^3
Specific heat	2	1092 J/kgK
	477	1215 J/kgK
	1027	1364 J/kgK
	1527	1429 J/kgK
	1927	1467 J/kgK
Viscosity	0	1.71e-5 Pa.s
	1927	3.55e-5 Pa.s

Table 2. Material properties of air

Property	Temperature	Value
Conductivity	All temperatures	2.563e-5 W/mmK
Density	All temperatures	Equation of state
Specific heat	All temperatures	1004 J/kgK
Viscosity	All temperatures	1.817e-5 Pa.s

Results of insert design types

The results of the simulations that were made to compare three major design versions were evaluated based on four parameters:

1. temperature of flue gas leaving the heat exchanger: the efficiency of a fireplace is calculated based on the flue gas temperature, leaving the system. The lower the temperature is, the more effective the fireplace will be.
2. temperature of air leaving the heat exchanger: the higher the air temperature is after the heat exchanger, the better the mixing with the hot wood gas will be inside the fireplace.
3. pressure loss on the flue gas side: since the whole system is driven by the p=12 Pa depression (standardized value) created by a chimney with average height it is very important to have the lowest pressure loss as possible.
4. pressure loss on the air side: same as with pressure loss on the flue gas side.

The following table summarizes the values of the above four parameters for the best performers of each major geometry versions:

Table 3. Results of the best performers of the tree major insert types

Heat exchanger insert type	Flue gas outlet temperature [°C]	Flue gas pressure loss [Pa]	Air pressure loss [Pa]	Air outlet temperature [Pa]
Cross-flow 12pcs d50 mm tubes	210.15	0.175	1.25	121.36
Spiral plate with 2.5 turns plus 5pcs d70 mm tubes	239.3	0.15	9	107.5
Spiral tube with 1.5 turns	246	0.23	7.8	83

Sub-versions of the best performer cross-flow tubular insert

From Table 3. it can be seen that the most promising insert type was the cross-flow tubular design so as next step, seven more sub-versions were created from the best performer 12 pieces of Ø50 mm tubes insert.

Each of them contained a change in a single parameter like increasing the tube diameters from Ø50 mm to Ø60 mm or increasing the length of tubes from L=200 mm to L=300 mm or decreasing it to L=110 mm. Table 4 summarizes the changes carried out based on the original cross-flow insert.

Table 4. Changes on the basic cross-flow insert type

Cross-flow sub-version name	Description of parameter change
Base design: 12pcs Ø50 mm tubes	Original design, best performer of the type comparison.
12pcs Ø50 mm tubes L=110 mm	Length of tubes decreased to 110 mm.
12pcs Ø50 mm tubes L=300 mm	Length of tubes increased to 300 mm.
12pcs Ø50 mm tubes drum Ø=260 mm	Outer diameter of drum was decreased to 260 mm.
12pcs Ø50 mm tubes drum Ø=400 mm	Outer diameter of drum was increased to 400 mm.
12pcs Ø50 mm tubes new arrangement	New tube – the so-called chessboard - arrangement.
12pcs Ø60 mm tubes	Tube diameter was increased to 60 mm.
12pcs Ø40 mm tubes	Tube diameter was increased to 40 mm.

Results of cross-flow sub-versions

As we did it with the type comparison part of the project, we also made computational fluid dynamics simulations for all sub-versions of the cross-flow type insert. On the following figures temperature results can be seen on cut planes of some sub-versions. Table 5 summarizes all results.

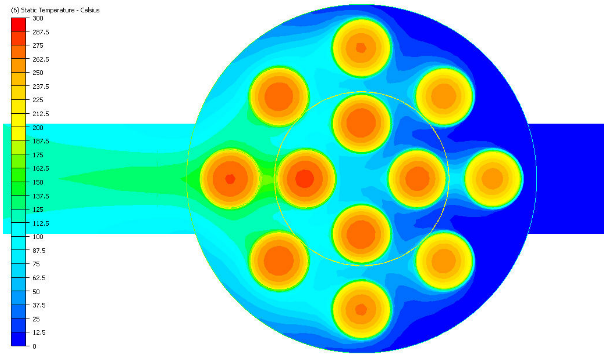

Fig. 8.a. Temperature in a horizontal cutplane of base 12pcs Ø50 mm tubes insert

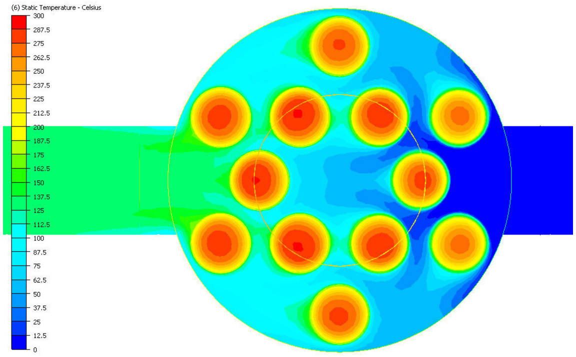

Fig. 8.b. Temperature in a horizontal cutplane of 12pcs Ø50 mm tubes with new arrangement

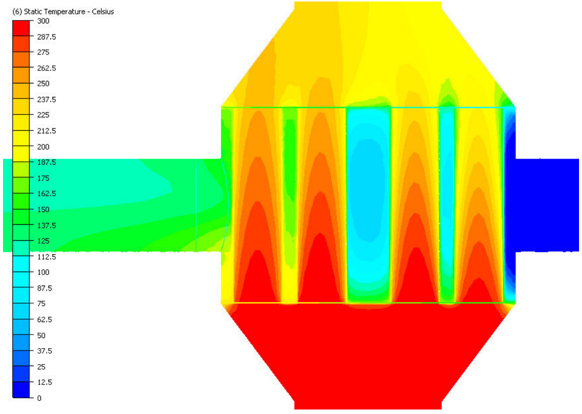

Fig. 9.a. Temperature in a vertical cutplane of base 12pcs Ø50 mm tubes insert

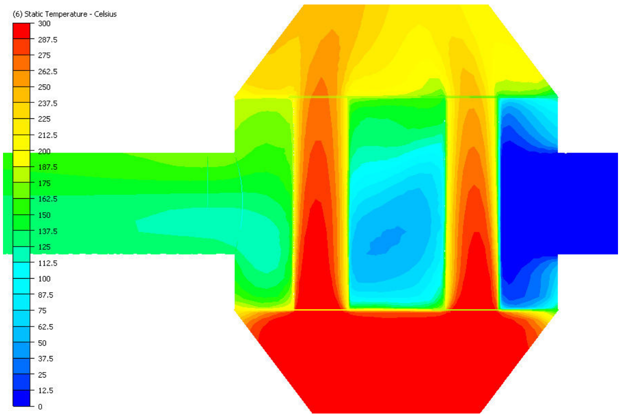

Fig. 9.b. Temperature in a vertical cutplane of 12pcs Ø50 mm tubes with new arrangement

Table 5. Results of cross-flow inserts

Heat exchanger insert type	Flue gas outlet temperature [°C]	Flue gas pressure loss [Pa]	Air pressure loss [Pa]	Air outlet temperature [Pa]
Base design: 12pcs Ø50 mm tubes	210.15	0.175	1.25	121.36
12pcs Ø50 mm tubes L=110 mm	244	0.085	1.56	98.1
12pcs Ø50 mm tubes L=300 mm	228.6	0.12	0.56	141.9
12pcs Ø50 mm tubes drum Ø=260 mm	237.2	0.32	1.7	119.7
12pcs Ø50 mm tubes drum Ø=400 mm	239	0.1	0.97	121.5
12pcs Ø50 mm tubes new arrangement	230	0.09	1.32	134.9
12pcs Ø60 mm tubes	232.3	0.03	2.03	124.7
12pcs Ø40 mm tubes	237.4	0.35	1.12	116.6

Optimization

As one can see on Table 5 there are parameters that counteract. For example if the length of the tubes was decreased to L=110 mm (from the basic L=200 mm) it helped the flue gas pressure loss, but all other parameters had worse performance. The same is true for enlarging the length of tubes to L=300 mm, it was helpful regarding air outlet temperature (increased to T_{air}=141.9°C from T_{air}=121.36°C) but flue gas outlet temperature was not as high as with the basic design. Because of that, in order to find the best parameter arrangement we decided to conduct an optimization process.

The optimization stage is currently ongoing. We decided to use the Simplex algorithm [2] because it requires small number of preliminary CFD simulations to build the initial data field and it requires fairly small number of iterations to reach optimum.

The aims of the optimization will be the followings; each of them will be weighted by a constant between 0 and 1 to represent its importance:

1. Minimum of flue gas temperature, because it is used to calculate the efficiency of a fireplace.
2. Minimum of pressure loss on the air side, since there is only p=12 Pa depression as standardized value to drive the air and flue gas flow.
3. Minimum of pressure loss on the flue gas side.
4. Maximum of air outlet temperature.

As constraints dimensional criteria for diameter and length of tubes and also a constraint for the minimum flue gas temperature to avoid moisture condensation in the steel structure and in the chimney will be applied. After the completion of the optimization process the heat exchanger will be CFD analysed again, it will be produced and results will be validated.

Summary

In this paper the authors presented the current results of an ongoing development project in which a heat exchanger is constructed for an 8 kW wood fired domestic fireplace. The aim of the project is to increase the efficiency of the fireplace by reusing the heat that would leave the system through the flue gas pipe. In the heat exchanger the temperature of the flue gas – which is the basis of measuring efficiency - is decreased and the air for burning the wood is preheated.

There were three major heat exchanger types analysed with computational fluid dynamics simulations and the best performer, the cross-flow tube design was further developed also with CFD. As result of this simulation process the temperature of flue gas was decreased by 30% (from 300°C to 210°C) and the air temperature was increased significantly (from 0°C to 141°C).

In order to find an optimum of flue gas and air temperatures and pressure losses on both flue gas and air side, aim functions and design constraints will be incorporated into the Simplex algorithm which will be used to find the best heat exchanger parameter set.

The authors would like to thank the support of the TÁMOP 4.2.1.B-10/2/KONV entitled Increasing the quality of higher education through the development of research - development and innovation program at the University of Miskolc.

References

[1] A.B. Palotas: Combustion calculations and basic data, *Lecture notes* University of Miskolc Department of Combustion Technology (2009)

[2] G. Dantzig: Notes on linear programming, *RAND Corporation* (1953)