Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 82 (2015) 245 – 251
Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

A CFD-based virtual test-rig for rotating heat exchangers

Alessandro Corsini[a], Giovanni Delibra[a,*], Giulio Di Meo[b], Mirko Martini[a], Franco Rispoli[a], Andrea Santoriello[b]

[a]Dept. of Mechanical and Aerospace Engineering, Sapienza University of Rome,. Via Eudossiana 18, 00184 Roma (Italy)
[b]Enel Energia e Ricerca S.p.A.

Abstract

Rotating heat exchangers are used in steel industry, air conditioning and thermal power plants to pre-heat air used in steam generators or for waste heat recovery. Here we focus on a rotating heat exchanger on a so-called Ljungström arrangement operated in thermal power plants to pre-heat the air fed to the steam generators. In these devices the heat exchange between two fluids is achieved through a rotating matrix that gets in contact alternatively with the two fluid streams and acts as a thermal accumulator. To increase the heat capacity and the overall exchange surface, the rotating matrix is filled by a series of folded metal sheets. In the paper we de-scribe a methodology to account for the effects of the Ljungström in a virtual test-rig implemented in a Computational Fluid Dynamics environment. To this aim, a numerical model based on the work of Molinari and Cantiano was derived and implemented in the OpenFOAM library. RANS numerical results were compared with those of a mono-dimensional tool used by ENEL to design Ljungström heat exchangers and validated against available measurements in a real configuration of a thermal power plant.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: rotating heat-exchanger, Ljungström, CFD, synthetic methods, OpenFOAM

1. Introduction

Rotating regenerative heat exchangers are used to recover waste heat in coal/fuel oil fired power plants. In a so-called Ljungström pre-heater, Fig. 1, two fluids exchange heat through a rotating matrix,Fig. 2, filled with pressed metal strips or wired mesh, Fig. 3, in order to increase the overall heat transfer. As the matrix slowly revolves (1-3 rpm), the same section is alternatively crossed by the hot flue gas and then by the cold stream of air. In this way, the matrix acts as an intermediate medium between the two separate streams. A series of seals guarantee that leakage between the fluids is minimised. Each

* Corresponding author. Tel.: +39-06-44585231
*E-mail address:*giovanni.delibra@uniroma1.it

Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.12.029

azimuthal portion of the matrix (sector) will be nearly isothermal, since the rotation is perpendicular to both the temperature gradient and flow direction. Flow inside the matrix is fully turbulent. These heat exchangers are characterised by high efficiency due to the capability of the matrix to be heated up to almost the same temperature of the hot stream of gases[1]. In a typical layout of the plant the hot and the cold streams are in counter-current axial directions.

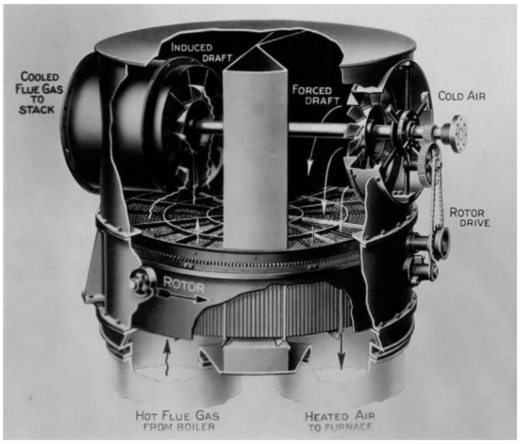

Fig. 1. Ljungstrom heat exchanger, wikipedia.org

Fig. 2. Rotating matrix of a Ljungstrom heat exchanger

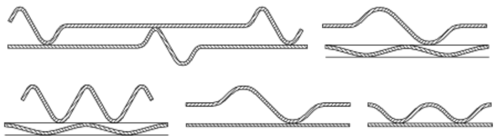

Fig. 3. Configuration of the heating elements inside the rotating matrix of a Ljungstrom [3]

The basic design of a Ljungström heat exchanger did not change much since the 1930s, as the benefits of operating at high efficiency come also with an arrangement that fits auxiliary components (the drive mechanism, the sealing adjusters and the bearings) outside of the rotating matrix. Therefore it is possible to inspect and maintain the device even when the heat exchanger is working [1].

The main criticalities of a Ljungström regenerative air pre-heater are related to the profiles of the heating elements. In fact these need to be chosen:

- to minimize the pressure drop in order to require smaller ancillary blowers to maintain draft in the fluid streams;
- to guarantee possibility of cleaning the matrix and remove the ashes, to avoid fouling and corrosion due exposition to the stream of flue gas [1] and in particular to sulphur oxides.

For these reasons, some Ljungströms are characterised by different topology of the heating elements on the hot and the cold side (these being identified axially, respectively with the side from which the hot stream and the cold streams enter the heat exchanger).

Other criticalities are:

- the choice of the sealing used to minimise leakage from a fluid stream to the other, as, due to the rotating mechanism, it is not possible to guarantee a full seal between the fluids. In particular this is

due to the combined effect of rotation, thermal cycling and large dimensions that result in a strong deformation of the rotating matrix during operations;
- the choice of the materials of the heating elements that are required to stand thermal shock, creep [1] and, above all, corrosion[2]. Flue gas in fact enters the Ljungstrom at higher temperature with respect to that of the desulphurization system, that therefore can only be used downstream of the pre-heater. In some cases, special alloys or even ceramics are used for the heating elements, in others special coatings are used on the most critical elements exposed to the hot stream.

Minor variations of the typical arrangement of a Ljungström consists in a tri- or four- sector heat exchanger, where the surface is divided in more sectors to split the cold air in two or three different streams[1] to allow for different thermodynamic conditions in the different streams.

Design, operations and heat exchange efficiency of Ljungström pre-heaters were widely investigated over years. Basic empirical design is discussed in[3], [4] and [5]. Numerical models for heat transfer based on finite elements or finite volume integration of partial differential equations are proposed and discussed in[6], [7], [8] and [9].In particular, in[9], Molinari and Cantiano[10] derived normalised temperature distribution in a Ljungstgrom following the methods of Willmott[11]-[12], Lambertson[13]and Fridland[14].

Kays and London[15]correlated the geometry of a rotating heat exchanger and its rotational speed with the heat transfer efficiency.

In the following a numerical methodology based on these assumptions [9]-[15] will be discussed, implemented inside OpenFOAM and tested against experimental data.

2. Synthetic model for rotating heat exchanger

A core limit in the use of CFD for simulations of a complete power plant for energy production – or even a portion of it – is that mesh requirements for a full description of each device are simply too high and not affordable within an industrial process. This is especially true when dealing with a Ljungstrom, as its rotating matrix is filled with hundreds of narrow channels where air or flue gas flow in fully turbulent regime. To tackle this issue it is possible to use a synthetic description of the Ljungstrom, based on the implementation of a series of source terms into Navier-Stokes and temperature equations. This approach is widely used with other components, notable examples are actuator disks for fans and wind turbines[16], or porous media for filters [17].

Here we derived a synthetic description of the Ljungstrom based on the assumptions that the main effects of the heat exchanger onto the fluids are:
- straightening of the flow and pressure drop when crossing the matrix;
- heat exchange efficiency is a function of the geometry and rotational speed of the matrix;
- heat exchange between air and flue gas.

2.1 Pressure drop

Given the geometry of the Ljungstrom, the characteristics of the flow inside the matrix, it is possible to apply the hypothesis of a porous medium [17] that follows the Darcy-Forchheimmer law:

$$\vec{\nabla} p = -\frac{\mu\vec{V}}{K} - \rho\beta|V|\vec{V} \tag{1}$$

where K and β are coefficient that depend on the characteristics of the porous medium and can be derived by interpolation of known experimental data or data acquired during the operations of the plant.

2.2 Effects of rotation on heat exchange efficiency

Effects of rotation were modelled following Kays and London [15], who correlated the axial lengthand the rotational speed of the rotating matrix with the effectiveness of the heat transfer within the matrix, here expressed as $\varepsilon = Q / Q_{max}$.

2.3 Heat transfer

Molinari and Cantiano derived the axial distribution of normalised temperature $\Theta = (T-T_{air})/(T_{gas}-T_{air})$ along the axial direction of the Ljungstrom. This can be used to modify the temperature transport equation to account for the presence of the rotating matrix of the Ljungstrom.

3. Test case

The derived methodology was tested against experimental data provided by Enel, acquired on the operations of a tri-sector Ljungstrom heat exchanger with a diameter of 14.95 m and an axial length of 2.267 m. The surface of this device entails 180 deg for flue gas, 35 deg for primary air and 145 deg for secondary air. Rotational speed in nominal conditions is 0.6 rpm. All the operating parameters are known: mass flow rate and temperature at inlet and outlet of the three sectors, leakage from a sector to the others, composition and pressure drop of the three streams.

4. Numerical method

The incompressible Navier-Stokes equations were solved with a standard high Reylonds k-ε RANS closure. A source term into momentum equation calculated according to Darcy-Forchheimmer equation accounted for the pressure drop of the matrix[17]. Temperature equation was modified to account for the heat exchange with a source term calculated according to [10]:

$$\frac{dT}{dx_i} = -\frac{k}{\rho C_p}\nabla^2 T - \frac{1}{\rho C_p} h \frac{1}{D_h}\left(T - T_w\right) \qquad (2)$$

where k is the thermal conductivity of the fluid, ρ its density, C_p specific heat at constant pressure, h the convective heat transfer coefficient, D_h the hydraulic diameter of the heat exchanger, T_w the temperature of the rotating matrix.

4.1 Grid

The computational domain entails the two sectors corresponding to primary and secondary air, and extends upstream and downstream of the Ljungstrom to account for the inflow distortions due to the arrangement of the ducting inside the power plant. Grid independency was tested against pressure drop inside the rotating matrix of the Ljungstrom and was achieved with 0.9M cells in the primary air duct and 1.2 in the secondary air duct. Final results were achieved with an average y^+ of 65, with maximum peaks of 119. The maximum aspect ratio of the mesh was 21.

4.2 Numerical setup

Computations were carried out imposing the mass flow rates at the inflow of the primary and secondary air, constant temperature and a turbulence intensity TI = 5%. The convective scheme for all the transport equations was quadratic upwind (QUICK). The linearised system of equations was solved using the generalised algebraic multi-grid solver for pressure and conjugate gradient solver for all the other quantities; the convergence threshold was set to 10^{-7}.

5. Results

A validation of the model is summarised in Table 1, where CFD results are compared against available measurements in a real power plant. Results are presented as average temperature at the outlet of the Ljungstrom and overall pressure-drop inside the rotating matrix, for both the primary and secondary air circuits. In both cases the discrepancy is around 3% for both quantities, confirming the reliability of the approach. Similar results were obtained with a mono-dimensional analysis (not described here) carried out with an internal tool from Enel. With respect to this RANS provides further insights onto the effects of the Ljungstrom when fitted inside the system. In Fig. 4 streamlines are plotted for both primary and secondary air circuits and reveal the effect of the matrix onto the flow: secondary motions due to the high flow distortion at the inlet are ironed out by the passage inside the porous zone of the heat exchanger. Nevertheless the inflow distortion lead to a not-uniform distribution of velocity inside the Ljungstrom, that reflects in higher pressure drop concentrated in the axial region and in the outer casing region for the primary air circuit, while the secondary air circuit shows higher losses only towards the casing due to the different distribution of velocity.

Table 1. Primary and secondary air outlet temperature and pressure drop in the Ljungstrom matrix. Measurements vs CFD.

		Measurements	CFD	Δ
Primary air	T_{out} [°C]	324	313	-11
	Δp [Pa]	598	577	-21
Secondary air	T_{out} [°C]	338	331	-7
	Δp [Pa]	666	638	-28

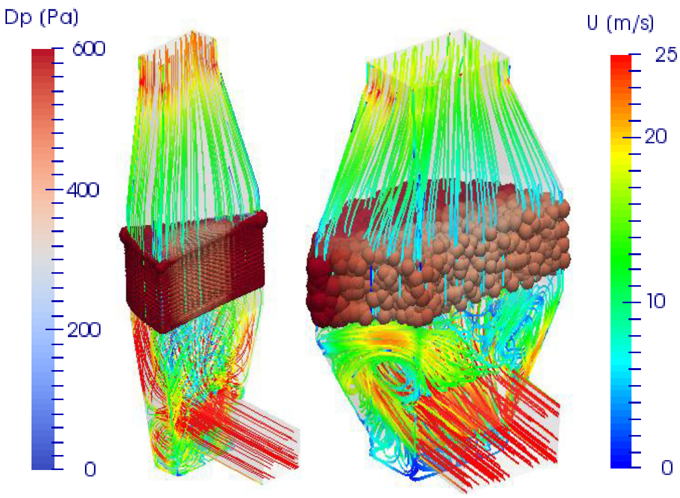

Fig. 4. Streamlines coloured with velocity magnitude and spherical glyphs coloured with pressure drop inside the Ljungstrom for primary (left) and secondary (right) air.

Conspicuously the difference in velocity of the flow reflects onto the heating of the air streams (Fig. 5), in particular leading to higher temperatures into the centre of the sectors, where the axial velocity is slower and the residence time inside the matrix increases.

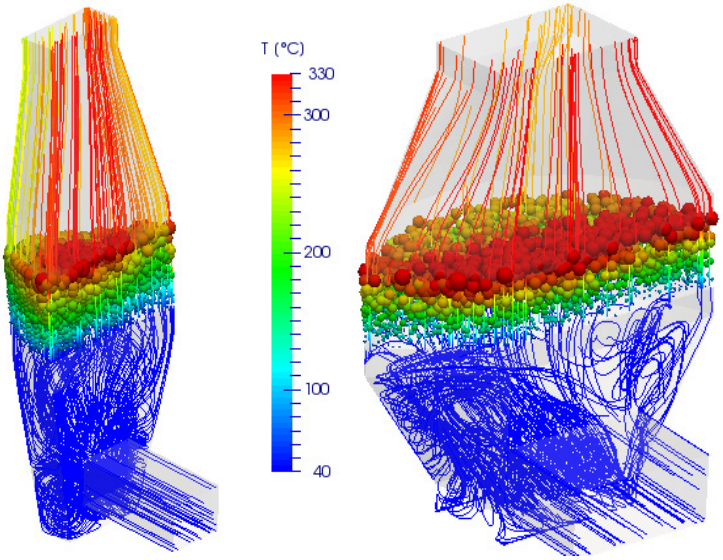

Fig. 5. Streamlines coloured with temperature and spherical glyphs coloured with temperature inside the Ljungstrom for primary (left) and secondary (right) air.

6. Conclusions

A synthetic model for a Ljungstrom heat exchanger was derived and implemented in the OpenFOAM library. The model was validated against available measured data acquired during operations of a power plant, proving its capability of predicting the temperature of the air streams at the exit of the Ljungstrom and the average pressure drop inside the matrix of the heat exchanger.
With respect to basic monodimensional tools, the implementation inside a CFD code allows to study the temperature difference inside the matrix due to non-uniform inlet velocity distribution.
As the computations are quite fast and do not have high hardware requirements, this approach is suitable to be used in order to study different configurations of the ducting arrangement at the inlet of the Ljungstrom in order to maximise the effectiveness of the heat exchanger.

References

[1] Thulukkanam, K. Heat Exchanger Design Handbook, Second Edition.

[2] Mac Duff, E.J., and N.D. Clark. “Ljungström Air Preheater Design and Operation. II. Corrosion and Fouling.” Combustion; (United States) 47:9 (1976)

[3] Kern, D. Q. Process heat transfer. McGraw-Hill, 1950.

[4] Rohsenow, W. M., Osipova, V. and Sukomel, A. Heat transfer. 1969

[5] Leontiev, A. Theorie des exchanges de chaleur et de masse. 1985.

[6] Kakac, S., Liu, H. and Pramuanjaroenkij, A. Heat exchangers, third edition. CRC press.

[7] Willmott, A. J. Digital computer simulation of a thermal regenerator. Int. J. of heat and mass transfer, vol. 12 1969, pp. 1291-1302

[8] Patankar S. V. Numerical heat transfer and fluid flow. McGraw Hill, 1980.

[9] Zhang C., Wieberdink, J., Simon T. W., Li P. Y., van de Ven, J. and Loth E. Numerical Analysis of Heat Exchangers Used in a Liquid Piston Compressor Using a One-Dimensional Model With an Embedded Two-Dimensional Submodel. Paper No. IMECE2014-38567

[10] Molinari, G. and Cantiano, C. Sulla distribuzione della temperatura negli scambiatori rigenerativi. Memorie del 40° Congresso Nazionale ATI, Trieste. Settembre 1985.

[11] Willmot A. J. Digital computer simulation of a thermal regenerator. Int. J. of Heat and Mass Transfer vol. 7, 1964.

[12] Willmott A.J. The regenerative heat exchanger computer representation. Int. J. of Heat and Mass Transfer vol. 12, 1969.

[13] Lambertson T. J. Performance factors of a periodic-flow heat exchanger. ASME Transaction April 1958.

[14] Fridland M. I. Calculation of rotary regenerative heat exchangers. Teploenergetika 22, 2975.

[15] W. M. Kays, A. L. London, Compact Heat Exchanger, McGraw Hill Co., 1984.

[16] Corsini, A., Delibra, G., Minotti, S. And Rossin, S., Numerical assessment of fan-ducting coupling for gas turbine ventilation systems. Proceedings of TurboExpo2015 - GT2015-42499.

[17] Bejan, A. - Convection Heat Transfer. Wiley, 2013.Van der Geer J, Hanraads JAJ, Lupton RA. The art of writing a scientific article. J Sci Commun 2000;163:51–9

Biography

Dr. Giovanni Delibra is research fellow at Sapienza University of Rome. His research is focused on numerical methods for industrial turbomachinery.