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PHD THESIS

RESEARCHES REGARDING THERMO-FLUIDODYNAMIC PROCESSES IN BURNERS AND FURNACES IN SWIRLING COMBUSTION

Abstract

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The aim of the thesis entitled "researches regarding thermo-fluidodynamic processes in burners and furnaces in swirling combustion" is a thorough knowledge of the mechanisms and factors influencing swirl combustion and conducting experimental research and numerical simulation, allowing to improve combustion process.

To this end were made:
- Experimental research using PIV technique;
- 2D and 3D numerical simulations of the nonreactive flow and reactive flow;
- Experimental study and numerical simulation for nonreactive flow and reactive flow for acoustic analysis of the swirl burner.

The paper is structured in seven chapters, summarized in the following:

**Chapter 1 - Introduction**

Chapter 1 presents an introduction to combustion and research methods used in burners and furnaces in swirling combustion.
Chapter 2 - The current state of research

Chapter 2 deals with theoretical and experimental knowledge essential to the phenomena of nonreactive and reactive swirling flow: turbulence, flow equations, methods used in solving these equations, flame structure and combustion modeling of turbulent flow. This chapter presents current state of research conducted worldwide on the topic.

Chapter 3 - Experimental research using PIV technique

Chapter 3 contains a description of the experimental setup, and experimental research carried out by the use of a technique for measuring mixture flow velocities: Particle Image Velocimetry (PIV). Using the PIV technique (fig.3.14) were determined: the absolute value of instantaneous velocities (fig.3.35), radial and axial component of velocity, and spatial distribution of velocity vectors. It was also determined the minimum number of sets of images required to obtain average values for velocity components, to identify the mean swirl flow in order to observe the appearance and evolution of such vortex structures, and location of the recirculation zones (fig.3.49, 3.53).

Fig.3.14 PIV system and swirl burner

Fig.3.35 Instantaneous velocity field

Fig.3.49 Instantaneous stream path for nonreactive confined flow

Fig.3.53 Mean stream path for nonreactive confined flow
Chapter 4 - Research conducted by numerical simulation in 2D

Chapter 4 describes the research conducted by numerical simulation in 2D, in Fluent. Were performed 2D numerical simulations of flow processes in burners and furnaces in swirling combustion. Have been studied the influence of swirl number on nonreactive flow and reactive flow and excess air in reactive flow through 2D numerical simulation.

Chapter 5 - Research conducted by numerical simulation in 3D

Chapter 5 presents research carried out by 3D numerical simulation in Fluent software. A 3D geometric model of swirl-burner assembly have been created at 1:1 scale (fig.5.3, 5.5), in which were performed three-dimensional numerical simulation (3D) of flow processes in both nonreactive flow and reactive flow. An 1.9 million tetrahedral mesh was used (Fig.5.7). Was made a program in which were defined inlet boundary conditions (Fig.5.16).

Fig.5.3 Burner head

Fig.5.5 Geometry of burner head used in numerical simulation

Fig.5.7 Mesh used in numerical simulation

Fig.5.16 Inlet boundary condition
Have been studied the influence of swirl number on nonreactive flow and reactive flow (fig.5.66) and excess air (fig.5.49) in reactive flow through 3D numerical simulation.

Fig.5.49 Mean axial velocity vectors at different distances (40, 80, 120mm) of the burner head for \( \lambda = 1.2 \)

Fig.5.66.b Izosurface of CO colored by temperature for \( S=0.4 \)

Fig.5.66.e Izosurface of CO colored by temperature for \( S=1.64 \)

Chapter 6 - Acoustic analysis of flame - experimental and numerical simulation

Chapter 6 contains experimental research and numerical simulation of nonreactive flow and reactive flow, for acoustic analysis. Dominant frequencies were found in nonreactive flow and reactive flow, and the validation has been carried out by comparison between experimental measurement results and those obtained by numerical simulation.

Fig.6.3 Frequency distribution for nonreactive flow

Fig.6.5 Geometry of burner head used in numerical simulation
Chapter 7 - Personal contributions and conclusions

Chapter 7 highlights the author's personal contributions and general conclusions.

Personal contributions:

- Experimental research of swirl flow in swirling burners, was performed by using modern methods of nonintrusive flow investigation - Particle Image Velocimetry (PIV) – a modern technique used in research worldwide.
- Experimental stand was built, experimental installation was performed to visualize swirl flow without reaction in a furnace and measurements were made using PIV technique to identify differences between the free flow of a swirl jet and a swirl jet in a furnace.
- Using the PIV technique were determined, the absolute value of instantaneous velocity, axial velocity, radial velocity and spatial distribution in the measuring plane of velocity vectors.
- Was determined the minimum number of sets of images required to obtain average values for velocity components in order to identify the mediated nature of swirl flow, in order to identify the appearance and evolution of vortex structures, the location of recirculation zones, and the correlations with numerical simulation.
- It was configured a parallel computing network which enabled numerical simulations in a shorter time.
- Were conducted a series of 2D numerical simulations, in Fluent, of flow processes through swirling burners and furnaces, in which have been identified a minimum number of quadrilateral elements for 2D numerical simulation, which meet the quality required of independent results for the geometrical mesh used.
- Was studied the influence of swirl number and air excess on the reactive flow through 2D numerical simulation.
- Was developed a 3D geometric model, 1:1 scale, of the studied swirl burner assembly. Were conducted a series of 3D numerical simulations, in Fluent, of flow processes through swirling burners and furnaces, in which have been identified a minimum number of tetrahedral elements for 3D numerical simulation, which meet the quality required of independent results for the geometrical mesh used.
- Was studied the influence of swirl number on the nonreactive and reactive flow and the influence of air excess on the reactive flow through 3D numerical simulation.
- The results obtained by 2D and 3D numerical simulation were validated by comparing them with the results obtained by PIV technique.
- It was written a software program to define boundary conditions for primary air, which allows the imposition of tangential velocity, which will generate the swirl flow.
- Numerical simulations were performed in 2D and 3D in order to identify the limit introduced by 2D models, in swirling flow.
- Numerical simulation of the nonreactive and reactive flow showed the swirl number necessary for the appearance of the vortex breakdown phenomena.
- Experimental setup was performed for acoustic flow analysis of nonreactive and reactive flow in a nonpremixed swirl burner.
- Numerical simulations of were made in for acoustic analysis. Dominant frequencies were identified in the nonreactive and reactive flow, and the validation was made using noise correlations between the experimental results and those obtained by numerical simulation.
- There have been generalization and interpretation of the results, in order to apply the findings, both the existing typologies of vortex burners, and the design of vortex burners in November.
- Generalization and interpretation of the results achieved when applying these research, both on existing swirl burners typologies, and the design of swirl burners.
General Conclusions
Experimental investigation using PIV technique revealed the following:

- Minimum number of sets of images necessary to capture the mean flow for a swirl dominated flow is 500.
- The instantaneous images can be captured to highlight the central flow recirculation of the burner head, and multiple vortex type structures which develop both sides of the jet. Local external recirculation zones are not present after mediation, because of the nonstationary flow. The medium flow highlights only permanent structures such as central recirculation zone which develops due to the swirl flow.
- By comparing the results obtained in a free jet and those obtained in a constraint flow, using PIV technique, I made these observations: external circulation areas are present in stream flow in the constraint jet and free jet, but in the constraint flow, vortex structures that form by both sides of the flow will be larger and more frequent, resulting in an increase of external recirculation. Central toroidal recirculation zone in the burner head is present in both cases, but will be more intense in the constraint flow case.
- Also, in the mean flow I observed a slight asymmetry on the right side of the burner towards the left side. This asymmetry comes from the construction of the burner and can be seen clearly in all the mediated flow charts, in all PIV measurements performed on the burner, both in the free flow and in the constraint flow.

Numerical simulation investigation led to these conclusions:

- Minimum number of elements for 2D numerical simulation, in the swirl flow studied, which meets the necessary quality mesh for independent results is 111,000 quadrilateral elements and the for the 3D flow, were used 1.9 million tetrahedral elements.
- Validation in both 2D and 3D cases of swirling flow was done by comparing the results obtained by numerical simulation with results obtained by PIV investigation. The turbulence model used for numerical simulation, with the results closest to those measured by PIV technique, in both 2D and 3D cases was RNG k-ε with module swirl dominated flow enabled.
- 2D numerical simulation study is not recommended for swirl flow, both nonreactive and reactive flow. Therefore, it is recommended to use 3D geometric models in numerical simulations of swirling flow. Results drawn from this analysis have shown that 2D geometric models, shows similarities with the 3D, just in case of flow without swirl.
- It recommends a swirl number of S>0.6 if desired the occurrence of vortex breakdown.
- The maximum temperature at the exit of interest domain is 1250 °C for an amount of excess air of λ=1.05. For λ= 0.9-1 temperature value is lower due to rich fuel mixture that makes the combustion incomplete, and for λ = 1.2-2 temperature value is lower due to dilution of combustion gases with more air.
- Therefore vortex breakdown is leading to creation of a central toroidal recirculation zone. This recirculation zone is important in the case of these types of burners because of the recirculation of the final and intermediate products of combustion, which have a higher temperature. This causes the mixture to be faster, doing preheating and flame stabilization near the burner throat.
The advantage of bringing final product of the reaction in the mixing zone is to lower flame temperature due to dilution of the fuel with air, in effect lowering thermal NOx.

The advantage of bringing the intermediate product of reaction in the mixing zone is to increase their residence time in the flame, and consequently, complete combustion of fuel mixture.

Along with increasing the swirl number, external recirculation zones are positioned closer to the burner head, bringing in the mixing and reaction zone the final and intermediate product, doing preheating and flame stabilization near the burner throat.

By increasing the swirl number, there is an increase of turbulent kinetic energy in the mixing zone, leading to an improvement in fuel mixture.

By increasing the swirl number, turbulence intensity will increase, leading to increased burning rate, flame length will decrease accordingly, and its width will increase, resulting in smaller furnaces.

The results obtained by applying the turbulence model RNG k-ε with swirl dominated flow activated, applied to 3D swirling shows similarities with results obtained by PIV technique, but the internal recirculation zone position is not very well represented, as guides to adoption of other models of turbulence, more costly in terms of computation – Large Eddy Simulation (LES).

Conclusions emerged from acoustic analysis of a swirl jet in reactive flow are:

- Occurrence of a frequency of 43Hz, both in experimental measurements and in numerical simulation results. This frequency is generated by the nonreactive flow of the mixture.
- From experimental measurements for the reactive flow, was recorded a dominant frequency of 300Hz. Sound spectral analysis, performed according to the excess air, show that dominant frequency does not depend on the excess air, but the spectrum width depends on it. Also, a frequency of 300Hz was found in the case of numerical simulation of the reactive flow. This frequency is the frequency of the internal combustion chamber. Frequency of 300Hz can be found on the experimental measurements for nonreactive flow, but at a much lower amplitude. After the combustion reaction is initiated, the amplitude of this frequency increased of 300 times. Some other frequencies were determined: 240, 260, 280Hz. Frequencies surprised by numerical simulation are 6, 47 and 236Hz.
- The experimental analysis performed on swirl flow revealed its strong nonstationary nature for nonreactive flow, and more so in the case of reactive flow, because of the thermoacoustic instabilities. Also, the numerical simulation of swirl flow was concluded that both the nonreactive flow case, and the reactive flow are nonstationary. In the reactive flow case, instability is accentuated. This observation confirms the conclusion that led to conduct numerical simulation to analyze flow in a swirl burner in 2D and 3D (Chapters 4-6), in the nonstationary regime.