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Investigation of the nonreactive flow in a swirling burner

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1. Introduction

The present study focuses on studying nonreacting flow in a nonpremixed swirl burner. In order to reduce harmful emissions, the current trend in burner designing is to operate under fuel lean and swirl combustion. However, successful designs require a detailed knowledge of the combustion process. In the nonpremixed case combustion efficiency and pollutant emissions of gas burners are strongly influenced by the fluid dynamics that controls mixture formation and chemical reactions [1].

Today, the reduction of pollutant emissions from fossil fuel combustion process is one of the important aims of scientific research and this problem arise strictly from fluid dynamics of the mixture. Swirling flow contributes to a better and fastest mixing of methane with air because of the induced turbulence and when the burning is taking place provides the flame stabilization [2]. Natural gas is considered as a clean fuel compared to the other fossil fuels, but formation of unwanted pollutants, such as nitrogen oxides, are still taking place while burning this fuel. Under lean combustion conditions, the peak temperature is reduced, NOx emissions are lower, but high CO emission levels, flash back and flame blow out, may occur.

The phenomena are very complex as many physical, time and chemical scales are involved, therefore turbulent combustion instabilities multiscale 4D problems (space and time), like vortex breakdown and vortex precessing core [3, 4], appear.

Direct evaluation in a nonintrusive way of the flow pattern in nonreacting flow in a swirl burner is of great significance, both from the design point of view and the modelling of the combustion devices with Computational Fluid Dynamics (CFD) software and with modern experimental investigation techniques like Particle Image Velocimetry (PIV).

Numerical simulation of turbulent combustion is particularly difficult, as the phenomena involved are highly nonlinear and unsteady. In addition, a direct full simulation of the problem (Direct Numerical Simulation - DNS), now, is beyond our computing capability. However, the recent increase in computational power enables to simulate only the largest scales of turbulence and capture the possible instabilities with Large Eddy Simulation (LES) [5-7]. The formulation of LES equations and models is a difficult and unsettled aspect of turbulence simulation research, and so there are several LES approaches. We will use the classical approach in which the Navier-Stokes equations are formally filtered and subgrid models for unknown terms are employed [8-10]. Unfortunately, even the best current LES modelling techniques do not provide reliable and accurate quantitative predictions in the complicated flow situations encountered here, so, the numerical simulations will be validated by an PIV experimental investigation method.

Particle Image Velocimetry measures whole velocity fields in a plane by taking series of two images at a specified time one after each other (Fig.1). In this way PIV system determines the magnitude and the direction of the velocity field.

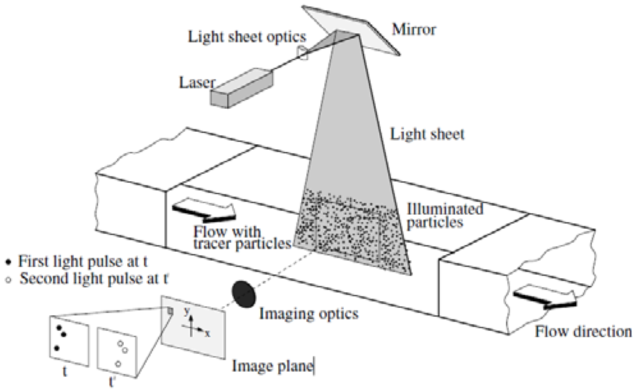

Fig. 1 Experimental arrangement for PIV [11]

As reported in many previous works [12, 13], the fuel injection procedure has a strong impact on pollutant formation and the PIV technique is very useful in order to gain information on mixing products between reactants and to put in evidence the interaction between the fuel jet and the surrounding stream [14].

2. PIV measurement

Since the flow can be quite fast we have to avoid blurred images and that is one reason to use laser pulses. One laser pulse width is only ~10 ns long. The other reason is that the laser light can be focused into a thin light sheet (~1mm) so that only particles in that plane are excited. Otherwise the scattered light from particles in other planes would make this measurement impossible.

The PIV system is composed from a LaserPulse Dual Nd: YAG laser at 120 mJ/pulse and at a maximum rate of 15 Hz. For this experiment a spherical lens with focal length of 500 mm and a cylindrical lens with the focal lens of -25 mm (equivalent to a divergence angle of 25°) have been used. Digital camera was a model Power-

View Plus 4M, with the resolution of 2048x2048 pixels, with a 15 frames/sec. A special device – LaserPulse Computer Controlled Synchronizer with triggering channels – composed from a computer and a synchronizing device is utilized so that it can synchronize lasers with the camera. The system can store the first image (frame) fast enough to be ready for the second exposure. This can be done with the entire PIV system in Frame Straddling mode.

The Frame Straddling mode is used when PIV images are acquired for the actual flow field measurements. The control of the Frame Straddling mode is performed in the INSIGHT 3G software, delivered with PIV system. When the camera is set at the Frame Straddling mode, the camera takes two consecutive image frames as one image capture. The timing between the laser exposure and in these two consecutive images is determined from Insight 3G software. Minimum frame straddling time is 200 ns and for this case was set to 20 μs. Laser A power has been set to 70 mJ/pulse and Laser B to 50 mJ/pulse. As tracing particles we used smoke.

In Fig. 2 the PIV system and swirl burner assembly used for the experimental investigation is presented.

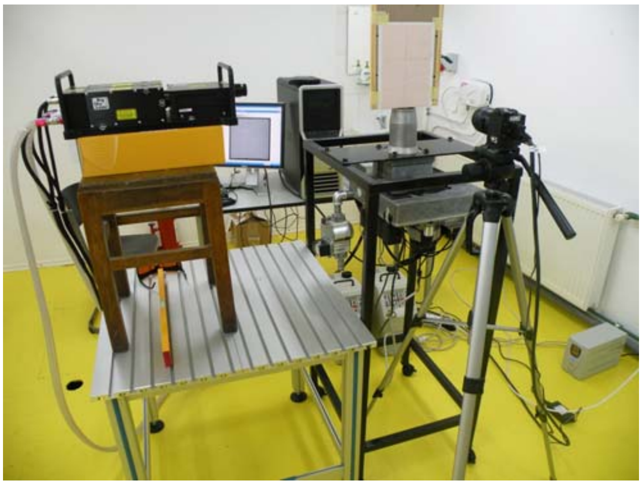

Fig. 2 PIV system and swirl burner

PIV system is taking two consecutive images made in Frame Straddling mode. No significant differences can be made only by eyes in these two images. The application Insight 3G is able to see thin differences between these images, and can establish the direction and magnitude of the velocity vectors (Fig. 3).

After the calibration of the PIV setup, the software is able to deliver the values of the velocity vectors field. From the measurement have resulted 2448 vectors, 2372 of them have been precisely determined, only 76 of them have been obtained by interpolation of the neighbouring vectors, this number represents 3.1% from the total number of vectors.

Experimental results obtained with the PIV system, have been first processed with the application offered with the system, Insight 3G, but the post processing is realized in Tecplot application. In the figures below instantaneous velocity fields on the isothermal case flow of the air after the burner throat can be seen.

A principal advantage of PIV is its capability to provide information about the instantaneous flow field. In Fig. 4 an instantaneous velocity field is presented.

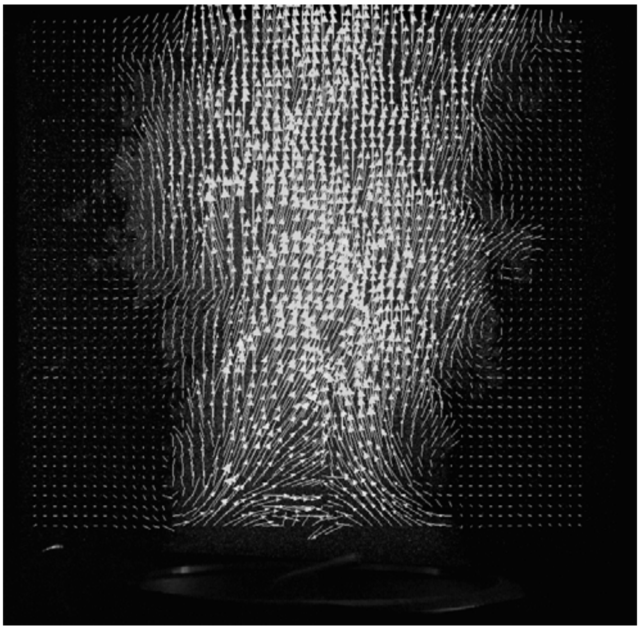

Fig. 3 Processed PIV image

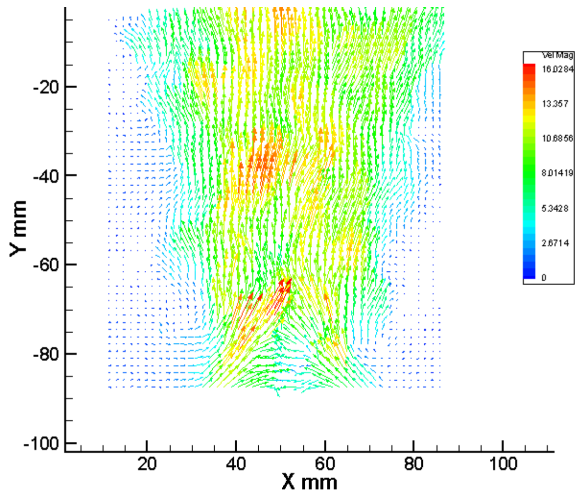

Fig. 4 Instantaneous velocity field

In Fig. 5 instantaneous axial velocity vectors for the same isothermal flow are plotted. A good observation of the intensity and positioning of the recirculation zones can be notified by taking account of axial velocity vectors

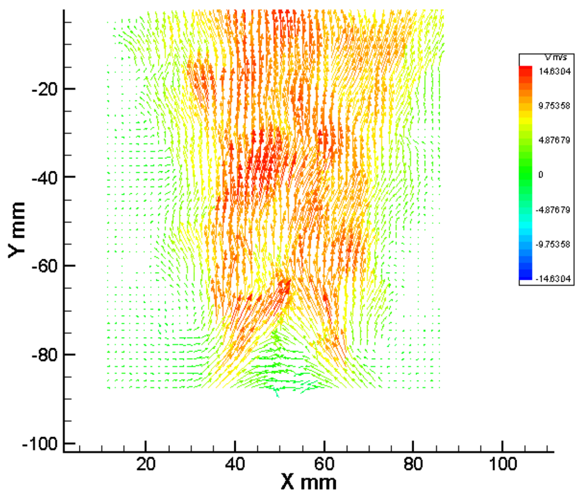

Fig. 5 Instantaneous axial velocity vectors

The PIV capability to provide information about the instantaneous flow field is well illustrated by the two sets of successive instantaneous images shown in Fig. 6 in which stream paths for the nonreactive flow of the air are represented. In the central region can bee seen a central recirculation zone formed after the burner and there appear to be a few vortical structures with variable positioning in the same areas.

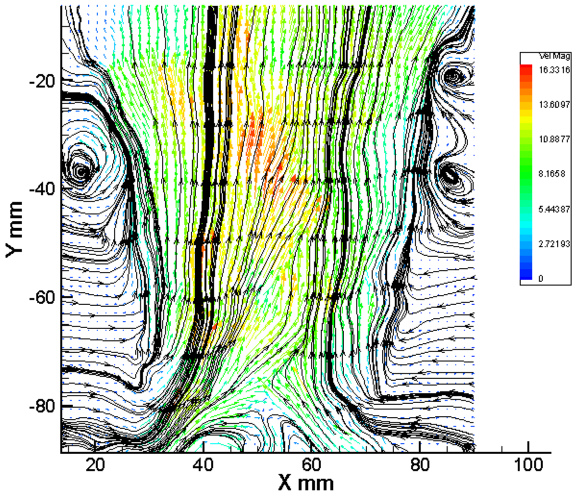

Fig. 6 Instantaneous stream path

Another advantage of PIV is its capability to provide information about the mean flow field.

Figs. 7-9 show typical time-averaged results. Averaging is done over 80 PIV images. In Fig. 6 mean velocity field over 80 frames can bee seen.

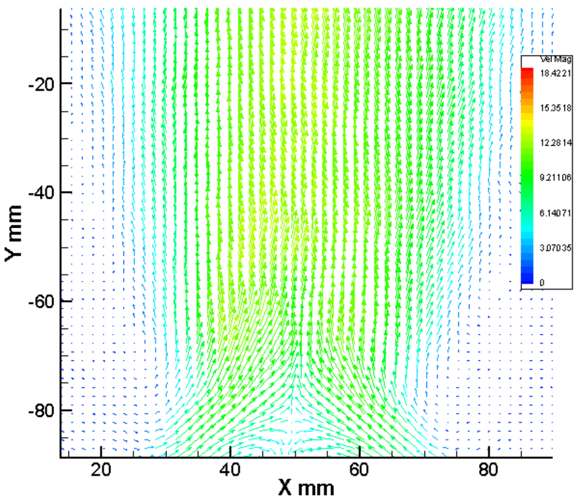

Fig. 7 Mean velocity field

In Fig. 8 mean axial velocity vectors are represented.

Fig. 9 shows well-defined mean stream paths and a zone of reverse flow in the burner head region.

From the mean flow we can identify the central toroidal recirculation zone as a permanent zone of recirculation, this area will rise when the combustion is taking place due to the gases expansion and possibly will cause a vortex breakdown. Vortices that are developing on the external jet flow (Fig. 6) are moving downstream. Even the instantaneous velocity fields are looking rather instable;

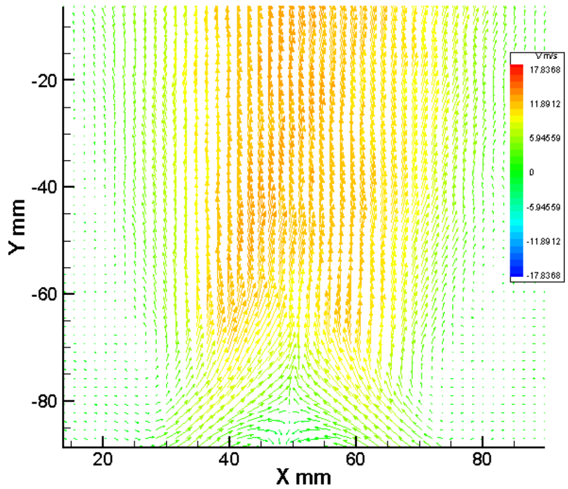

Fig. 8 Instantaneous axial velocity vectors

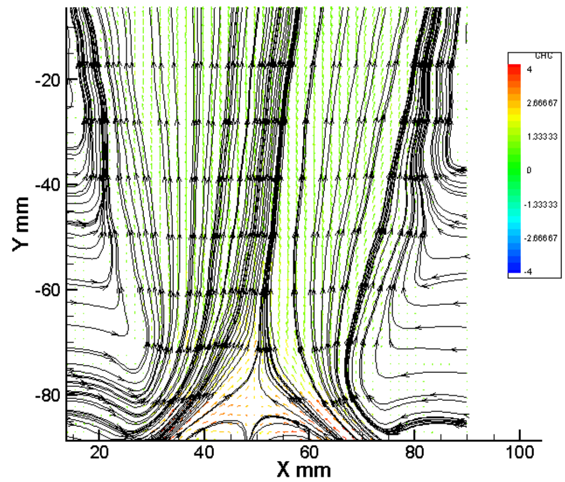

Fig. 9 Mean stream path

the mean velocity field is revealing that there is a stable flow.

3. Numerical simulation

Because of the advantages offered by the numerical simulation investigation method, the study of the swirl burner has been carried out through this method. Numerical results are validated by the measurements made on the same burner with PIV equipment.

The geometrical model is realized in Gambit [15], and the configuration is 3D one. The grid consists of tetrahedral and hexahedral elements, a high density of elements being constructed in the interest zone (mixing zone, burner head). The total number of cells is 0.9 million. The studies were performed by the use of well known CFD software FLUENT [16]. A segregated solver formulation was used for these computations (equations are solved sequentially instead of simultaneously as in coupled solver). Using a control-volume based technique. Fluent converts the differential governing equations to linear algebraic equations that can be solved numerically. The control volume technique consists in integrating the governing equations for each control volume by obtaining discrete equations that conserve each quantity on a control volume basis. The solver stores the discrete values of the scalars at the cell centres and in order to determine the scalars value between the cells centres, second order upwind scheme was used for interpolation. Regarding accuracy of results we have imposed 10^{-6} convergence criteria. The governing equations represent the conservation of mass, momentum (Navier-Stokes), energy and additional species. Fluid properties are calculated from local gas composition. The LES turbulence model with associated transport equations is applied to account for turbulence because of the different regions of the flow of low Reynolds number alternating with high turbulence zones. The mixture model used for this simulation is species transport with mixture material: methane-air-2step, but the chemical reaction is not initialized. The standard wall functions option for the near wall treatment was applied as well as the no slip condition at the wall [17].

This method requires huge computational resources. As a fact, to simulate the nonreactive flow in this case, on this geometry, for 0.5 seconds of flow, it was necessary 76 days of parallel processing on a parallel network composed from five PC quad cores with 4GBRAM each.

First, we create the geometry similar with the real one, we imposed the swirl condition from the air inlet boundary condition.

The numerical simulation was started with a time step, corresponding to a CFL number of 0.08. After solution stabilization the CFL number was raised to ~0.4, which corresponds to a time step of 10^{-6}seconds. The operating temperature and pressure where respectively 293 K and 101325 Pa.

Comparisons are made between instantaneous velocity field and time-averaged velocity field over 22500 consecutive time steps. First, we compared the instantaneous velocity values at different position in a transversal plane from the burner head (Fig. 10) with mean velocity values at the same distances from the burner head (Fig. 11). Instantaneous velocity values are scattered around the mean value due to the anisotropic influence of the swirl flow. In Fig. 11, mean velocity values at different distances from the swirl burner can be observed more clearly.

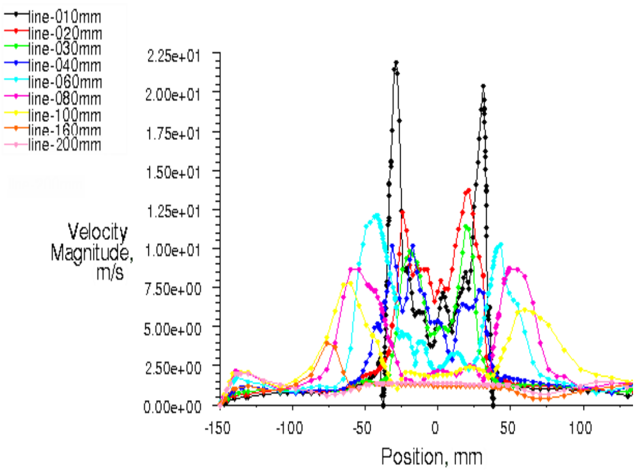

Fig. 10 Instantaneous velocity values at different distances from the burner head

In Figs. 12 and 13 we have compared instantaneous axial velocity values at different distance, in transversal planes, from the burner head with mean axial velocity values at the distances from the burner head. The values of

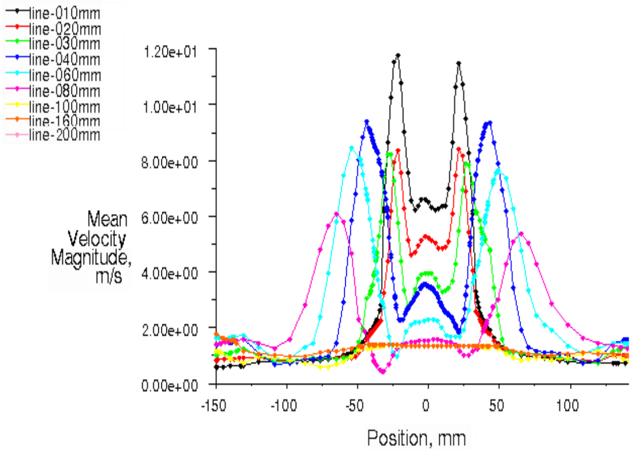

Fig. 11 Mean velocity values at different distances from the burner head

instantaneous axial velocities are generally higher than the mean value of the axial velocity, in some cases being almost double. Instantaneous axial velocity values are scattered around the mean value. Central recirculation zone can be observed clearly in Fig. 12. As comparison, the instantaneous axial velocities are in the same range with the values of mean axial velocity for the recirculation zone.

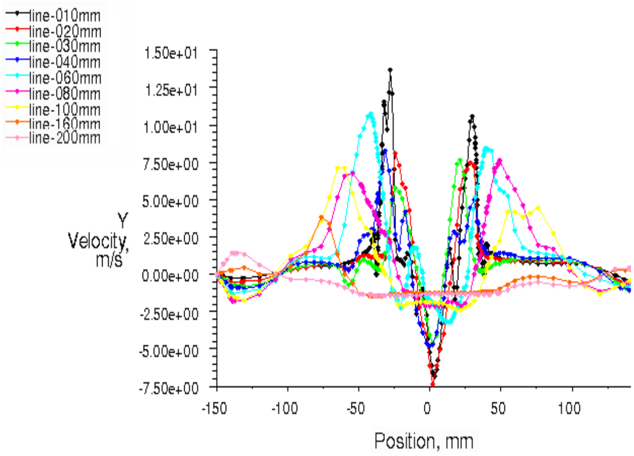

Fig. 12 Instantaneous axial velocity values at different distances from the burner head

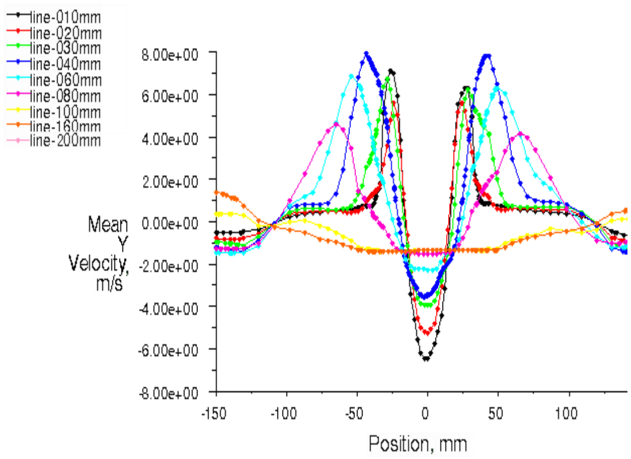

Fig. 13 Mean axial velocity values at different distances from the burner head

4. Conclusions

In all the instantaneous images taken by PIV measurements appears external recirculation zone at different positions.

Both, in numerical simulation and in experimental results, a central recirculation zone appears. This zone is maintaining own aspect over all the measurement time.

From quality point, the velocitiy values together with mean velocity are in agreement with measurement data. The values of the computed velocity are lower than the experimental measured one.

External recirculation zones appears both in numerical and experimental investigation diagnostic methods.

From the instantaneous stream path along all the captures, the conclusion is that external recirculation zones are appearing near the burner head, and are travelling downstream, away from this zone. In the instantaneous stream path a few vortices structures in the both sides of the current flow can be seen, but in the mean stream path image these vortices do not appear anymore because of the unstable character of the flow.

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References

1. **Araneo, L., Coghe, A., Cozzi, F., Olivani, A., Solero, G.** Particle image velocimetry, book chapter: Natural gas burners for domestic and industrial appliances. -Application of the Particle Image Velocimetry (PIV) Technique, ISBN 978-3-540-73527-4, 2008, p.245-257.
2. **Gupta, A.K., Lilley, D.G., Syred, N.** Swirl Flows. -Abascus Press, 1984.-475p.
3. **Lucca-Negro, O., O'Doherty, T.** Vortex breakdown: a review. progr. -Energy and Combustion Science, 2001, v.27, p.431-481.
4. **Syred, N.** A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems.-Progress in Energy and Combustion Science, 2006, v.32, p.93-161.
5. **Nogenmyr, K.-J., Fureby, C., Bai, X.S., Petersson, P., Collin, R., Linne, M.** Large eddy simulation and laser diagnostic studies on a low swirl stratified premixed flame. -Combustion and Flame, 2009, v.156, p.25-36.
6. **Mahalingam, S., Thévenin, D., Candel, S., Veynante, D.** Analysis and numerical simulation of a nonpremixed flame in a corner.-Combustion and Flame, 1999, v.118, Issues 1-2, p.221-232.
7. **Alekseenko, S.V., Dulin, V.M., Kozorezov, Y.S., Markovich, D.M.** Effect of axisymmetric forcing on the structure of a swirling turbulent jet. -International Journal of Heat and Fluid Flow, 2008, v.29, p.1699-1715.
8. **Peng, L., Zhang, J.** Simulation of turbulent combustion and NO formation in a swirl combustor. -Chemical Engineering Science, 2009, v.64, p.2903-2914.
9. **Kanga, D.M., Culicka, F.E.C., Ratner, A.** Combustion dynamics of a low-swirl combustor. -Combustion and Flame, 2007, v.151, p.412-425.
10. **Galpin, J., Naudin, A., Vervisch, L.** Large-eddy simulation of a fuel-lean premixed turbulent swirl-burner. -Combustion and Flame, 2008, v.55, p.247-266.
11. **Raffel, M., Willert, C., Wereley, S., Kompenhans, J.** Particle Image Velocimetry – A practical guide, Second Edition.-Springer, ISBN 978-3-540-72307-3, 2007. -448p.
12. **Olivani, A.** Thermo-fluid-dynamic analysis of methane / hydrogen / air mixture under reacting conditions by laser diagnostics.-Joint Phd.Thesis, Politecnico di Milano & Universite d'Orleans, 2006, p.12-32.
13. **Coghe, A., Solero, G., Scribano, G**. Recirculation phenomena in a natural gas swirl combustor. -Experimental Thermal and Fluid Science, 2008, v.28, p.709-714.
14. **Kačeniauskas, A.** Mass conservation issues of moving interface flows modelled by the interface capturing approach. -Mechanika. -Kaunas: Technologija, 2008, Nr.1(69), p.39-41.
15. 2001, "GAMBIT 2 User's Guide", Fluent Inc.
16. 2001, "FLUENT 6 User's Guide", Fluent Inc.
17. **Nakutis, Ž., Kaškonas, P.** An approach to pneumatic cylinder on-line conditions monitoring. -Mechanika. -Kaunas: Technologija, 2008, Nr.4(72), p.41-47.

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TEKĖJIMO BE ATGALINĖS REAKCIJOS SŪKURINIAME DEGIKLYJE TYRIMAI

R e z i u m ė

Sūkuriniam degikliui eksperimentiškai tirti buvo taikomi srauto dalelių greičio lauko matavimo (PIV) ir skaitmeninis didelio sūkurio modeliavimo (LES) metodai. Dėl skysčio dinamikos įtakos mišinio susidarymui ir cheminės reakcijos ši dviguba kontrolė atliekama tik nagrinėjant atgalinės reakcijos neturintį srautą. Tyrinėjamas momentinis srauto tekėjimo greičio dydis, ašinis greitis, trajektorija. Momentinio greičio lauko ir vidutinio greičio lauko vertės laiko PIV matavimo atveju skenuojant daugiau kaip 80 paeiliui einančių kadrų ir, taikant skaitmeninį matavimo metodą, 22500 paeiliui einančių laiko intervalų. Dėl sūkurinio srauto tekėjimo didelio nepastovumo pastebėta tam tikrų skirtumų. Skaitmeninio modeliavimo rezultatai palyginti su PIV metodu atliktų matavimų rezultatais. Nustatyta, kad abiem atvejais atsiranda centrinė recirkuliacinė zona, kuri išlaiko tam tikrą savo padėtį per visą matavimo laikotarpį. Kokybiniu atžvilgiu srauto greičio vertės atitinka matavimais nustatytą vidutinę greičio vertę.

F. Bode, C. Giurgea, V. Hodor, P. Unguresan

INVESTIGATION OF THE NONREACTIVE FLOW IN A SWIRLING BURNER

S u m m a r y

An experimental investigation method - Particle Image Velocimetry (PIV) and a numerical investigation method – Large Eddy Simulation (LES) - is performed on a swirl burner. Due to the strong influence of the fluid dynamics that controls mixture formation and chemical reactions the present study focuses on studying nonreacting jet. Velocity magnitude, axial velocity and stream path are investigated in instantaneous and mean flow. Comparisons are made between instantaneous velocity field and time-averaged velocity field over 80 consecutive frames in PIV case and 22500 consecutive time steps in the numerical case. There are some differences due to the highly nonstationary behavior of the swirling flow. The results from numerical simulation are compared to the results obtained through PIV diagnostic measurements. Both, in numerical simulation and in experimental results, a central recirculation zone appears. This zone is maintaining own aspect over all the measurement time. From quality point, the velocity values together with mean velocity are in agreement with measurement data.

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ИССЛЕДОВАНИЯ ТЕЧЕНИЯ В НЕРЕАКТИВНОЙ ВИХРЕВОЙ ГОРЕЛКЕ

Р е з ю м е

Для экспериментальных исследований вихревой горелки применен метод измерения скорости движения частиц потока (PIV метод) и числовой метод моделирования большого вихря (LES метод). Из-за динамических явлений в жидкости, их влияния оказываемого на образование состава смеси и химической реакции, представленные исследования сфокусированы только на исследовании нереактивного течения.

В работе исследовались моментная и средняя величины скорости течения потока, его осевая скорость и траектория. Осуществлен сравнительный анализ между моментным полем скоростей потока и его средней величиной по времени, измеряемой (определенной) при использовании метода PIV с последовательно идущими более чем 80 снимками и с использованием числового метода измерения с 22500 последовательно идущими интервалами времени. Из-за большой неустойчивости вихревого течения потока установлены некоторые несоответствия результатов измерения. Результаты, полученные числовым методом, сопоставлены с результатами, полученными применяя PIV метод.

В обоих случаях (при исследовании числового и экспериментального метода) установлено появление центральной зоны рециркуляции. Эта зона поддерживает определенное собственное положение во время всего периода измерения. Качественно величина мгновенной скорости потока сопоставима с его измеренной средней величиной.

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