QUALITATIVE COMPARISON OF COMMERCIAL AND OPEN SOURCE PARTICLE IMAGE VELOCIMETRY SOFTWARES

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To my future self

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SUMMARY

Complex chemical and fluid dynamic mechanisms present in combustion systems necessitate the validation of computational fluid dynamics (CFD) models using flow visualization and velocity field measurement techniques. Two cutting edge measurement techniques for reacting flows are planar-laser induced fluorescence (PLIF), which images combustion radicals within the flame, and stereoscopic particle image velocimetry (sPIV), which is a non-intrusive laser-based velocity measurement. These measurements and others are often synchronized and coupled together to gain a complete picture of flow field variation (i.e. pressure, temperature, velocity, etc.). The PIV measurement in particular poses a variety of challenges especially during the data processing phase which can be achieved using either commercial or open-source software packages. This papers explores the qualitative difference between each software with the intent of providing a recommendation on which form of software should be used. By understanding the types of software that should be used, one can develop lab infrastructure that maximizes the effectiveness of using said software.

CHAPTER 1

INTRODUCTION

Background

This thesis describes the comparison of open-source and commercial particle image velocimetry (PIV) software in combustion applications. Increasing needs to develop cleaner and more efficient power generation demand the creation of new technologies to meet stringent environmental regulations. Combustion is the most widely adopted form of power generation and leverages the oxidation of fuel to generate energy. Because combustion couples complex fluid mechanical and chemical phenomena, it is often insufficient to simulate a combustor using just computational fluid dynamic (CFD) models without experimental validation. Thus, experimental methods are used not only to validate, but also to inform refinement of the CFD models. There are a variety of means to measure the characteristics of a flow field; however, this thesis focuses specifically on PIV as a means of exploring both reacting and non-reacting flows.

Background on Particle Image Velocimetry

PIV measurements are taken by directing a laser sheet into a flow seeded with particles. The laser serves as a high speed pulsed illumination source, and its light scatters off of the seeding particles. The scattered light is captured by a camera that is synchronized with the laser, and which captures a series of images of the illuminated seeding particles as they are convected by the flow. These images are then processed using some software to provide vector fields that describe the motion of the flow. PIV is not limited to planar 2-component velocity vector field measurements, and can through a different experimental set-up be used to generate planar 3-component velocity vector field measurements. This form of PIV is referred to as stereoscopic particle image velocimetry (sPIV), which unlike PIV requires two cameras to capture the seeding particle images from two different angles. Once these images are captured, open-source and/or commercial software can be used to calculate velocities, and other velocity driven qualities of flow fields like vorticity.

The application of PIV in combustion poses unique problems because of its unique requirements. PIV in other applications uses liquid seed which consists of a liquid material atomized into the air. The laser sheet is then scattered off of this liquid seed. In combustion applications, this is ineffective because the heat release will evaporate, or burn, the liquid seed. Thus, solid seed, usually alumina or titanium dioxide, are used [3,4]. Furthermore, the experimental set ups for these flows require optical access that allows the laser to pass through windows in the combustor walls. These windows are typically constructed from fused silica (quartz), since traditional glass cannot be used due to the high temperature of combustion. Additionally, quartz has advantageous optical properties for many of the other popular combustion diagnostics. Despite its advantages, quartz windows (as do any windows) bring their own challenges, since they can distort the laser sheet as it passes through the window, and they can establish intense laser light reflections that obscure portions of the seeding particle images.

In some situations, there is saturation in the data. This occurs when the laser scattering is too intense such that it exceeds the sensitivity range of the camera. When attempting to process this data, the software will reveal large holes where no particles are "present". Some software will extrapolate, others will not. The problem with extrapolation is that it can provide issues when calculating flow characteristics from spatial velocity derivatives or integrals, such as circulation or vorticity. This extrapolation can smooth derivatives, or create noise where there is none.

Another flavor of planar PIV is known as dual-plane PIV, and it has its own unique data processing issues. For these set-ups, two-dimensional processing is an effective means for recreating volumetric flow fields. This is done by establishing two laser sheets that are parallel to each other (i.e. the images captured by two different cameras have parallel laser sheets with specified distance between them). Using knowledge of the spacing between the parallel sheets, software can assume mass continuity between the two planes, and calculate the velocity gradients between the two planes and then with a constant density assumption derive the volumetric flow field. This is a limited approach, and can create an artificial and incorrect representation of the flow field.

Considering the complex issues related to capturing PIV data, and the many different flavors of PIV setups, it is incredibly important to have software that can correct for distortions in data, or effectively pre-process data to provide meaningful final results. The goal of this thesis is to explore qualitative data processing differences between open-source and commercial PIV software.

Background on Commercial and Open-Source Software

In various industries, it is common for two types of software that perform similar functions to exist. The first of these is commercial software which are professionally developed to perform computationally expensive tasks. Commercial software is typically developed by larger companies, is relatively "turn-key," and is professionally supported. These software packages contain powerful tools that effectively allow for tasks to be completed, and a variety of options. Open-source software is similar in its purpose, but differs in that it is free and the source code is freely available. With the ability to access source code, one is able to create additional functionality for the software tool. The decision to use commercial or open-source software is solely dependent on the user needs.

Literature Review: PIV in Combustion Applications

Particle image velocimetry (PIV) is a powerful flow diagnostic technique used to explore the real-time flow characteristics of single- and multi-phase flows. PIV provides the user with a non-intrusive means for the analysis of a flow field; thus, it is effective because it does not disturb the very flow that it is trying to measure. PIV is generally used in both reacting and non-reacting flow studies to confirm computational fluid dynamics (CFD) models are providing accurate data. Because of the reliability of this technique, researchers have begun to apply this technique, with modifications, to high pressure and high temperature reacting flows in order to provide similar validation of CFD models for these applications [1,2,3,4,5].

The vast majority of applications of PIV in the field of combustion is to explore the combustion instability problem, and to elucidate the dominant fluid dynamics in practical combustors. Thus far, however, there has been limited application of PIV to other aspects of combustion research, such as the study of turbulent flame speeds of synthesis gas fuels. The turbulent flame speed and the flame brush thickness are key parameters for computational fluid dynamics (CFD) models [1]. Several qualitative trends in the turbulent flame speed have been experimentally demonstrated, such as: (a) an increase in turbulent flame speed with increasing turbulent intensity, and (b) effect of pressure on the turbulent flame speed [2]. However, quantitative predictive capability for turbulent flame speeds as these parameters are varied, and as fuel composition is varied, does not exist. As such, implementation of many types of CFD models for un-characterized fuels or conditions is problematic. For example, fuels such as synthesis gas which is a mixture of hydrogen and carbon dioxide, do not have a well-populated turbulent flame speed database. Therefore, there is a need not only to measure turbulent flame speeds, but to study the underlying fluid dynamic phenomena so that engineering correlations may be developed. This strongly motivates the use of PIV and other flow diagnostic techniques when developing CFD models that involve alternative fuels.

PIV is also extremely useful in the development and testing of spray burners. In gaseous applications, the gaseous fuel and air mix together without causing any significant flow disturbances. Spray burners, however, add liquid fuel into the air changing the fluid mechanic behavior and complicating flow characteristics. By applying PIV to these burners, one is able to better design burners to facilitate complete combustion, and improve emissions [5].

Present Work

The current study explores post-processing options for PIV data obtained in turbulent, reacting flow fields. These data are extremely valuable, as they are used to validate and refine CFD models of real-world combustors, and they are also used to measure key parameters such as the turbulent flame speed. These data are difficult to convert from raw data to useful velocity vector fields, however, due to the extraordinary computational expense of implementing the PIV algorithm. Therefore, the present work explores the plethora of options for post-processing of PIV data so that researchers may embark on this difficult and expensive journey with the most appropriate tools for the given application.

CHAPTER 2

METHODS AND MATERIALS

In order to evaluate the efficacy of both the software available, this project analyzed data from an experimental campaign at the Ben T. Zinn Combustion Lab that explored turbulent flame characteristics of high hydrogen content (HHC) fuels on a low swirl burner (LSB). HHC fuels show great promise in the reduction of both carbon dioxide and NO_x, and LSBs are currently implemented as a means to further reduce the production of NO_x [6].

The primary characteristic of concern during this campaign was a measurement of the turbulent flame speed. This parameter is a measure of how fast the reactants are propagating through a flame front. The experimental facility features a LSB with a turbulence generator that allows for controlled and consistent turbulence intensities via a blockage ratio. Although a variety of measurements were taken on this facility, the primary use of PIV in this campaign was to characterize the mean and turbulence profiles of the LSB. Because of the in- and out-of-plane velocity campaigns characteristic of these burners, stereoscopic PIV was used to create the images below.

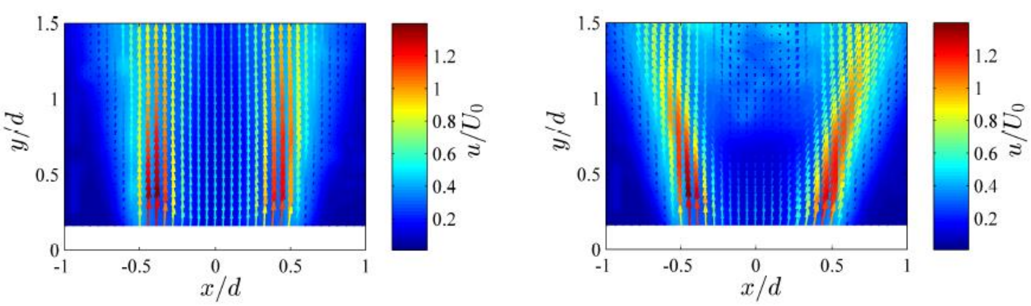

Figure 1: Mean velocity normalized by bulk velocity for non-reacting (left) and reacting (right, 100% CH_4, φ = 0.9) cases at STP. Bulk velocity is 20 m/s. Swirl number is 0.59. Blockage Ratio is 69%.

Using this case, commercial and open-source software are then evaluated based on the user interface, software capabilities, and quality of results.

Because this is a first order qualitative analysis, the Pugh evaluation methodology is used to compare each of these software using the commercial software as the baseline. The Pugh methodology allows one to compare a variety of criteria against a baseline. An option is give a “-“ when less favorable than the baseline, a “+” when more favorable than the baseline, and a “S” when neither more or less favorable. Once each option is evaluated, the number of pluses, minuses, and “S” are tabulated, and then added together. The plus has a value of one, the minus has a value of negative one, and the “S” has a value of zero. The ideal option is then the one with the highest score. Of the software being evaluated, the commercial software will be used as the baseline because of its prevalence in current research operations and will thus be referred to as the datum.

CHAPTER 3

QUALITATIVE ANALYSIS

The User Interface

Evaluation of the user interface is based on the ease of navigation, usability, and error tolerance. The ease of navigation is a measure of how challenging it is for a user to explore the various functions of a software. The usability is a measure of how well a user is able to fully utilize the software to complete a specific task. Lastly error tolerance is the ability for a user to troubleshoot an error made based off of prompts from the software.

Generally, commercial software will use a graphical user interface that has similar characteristics to the Windows user interface. Open-source software, however, will often have a unique interface that depends on the language used to implement it. The open source interfaces tend to have less features, making it easier to navigate. However, this limits their usability, where the myriad options available for commercial software make it simple for users to complete a designated task. Furthermore, the open-source nature of said software creates unique challenges when troubleshooting errors. Specifically, commercial software provide clear error designation which is often coupled with a direct means to address that error. Open-source software, on the other hand, will render errors in the environment of the respective language in which it is implemented. This often leads to erroneous errors that make little sense to the user, unless that user has prior experience or exposure to that platform.

Software Capabilities

Software capabilities focus primarily on image importing, image preprocessing, processing speed and calibration ability. How images are imported is important when considering directory structures. Image preprocessing is a crucial capability when attempting to rectify any data capture issues or to improve the quality of processed data. Processing speed is an important metric as it is important in planning projects. Calibration ability is important when ensuring data processed generates the correct values.

In both commercial and open-source software, the raw image importing process is directing the software to a specific directory where those images are located. Commercial software generally come equipped with powerful preprocessing packages, while open-source software will often require supplemental software to preprocess images. Furthermore, certain preprocessing packages are incompatible with specific open-source software requiring compatibility of those packages to be considered when using such software. Commercial software will often allow the user to evaluate the effect of preprocessing affects the raw data by providing a test window.

When planning projects and organizing research groups it is crucial to consider the expected completion time making processing speed an important parameter. For the same data sets, the commercial software was slower than the open-source software. This can be expected because of the greater software capabilities and computational needs of the commercial software. Some commercial software has the ability to leverage more than one computer to distribute the processing load and accelerate the processing speed.

The ability to calibrate is crucial, because it directly affects the flow velocities. Without calibration, the velocities are displayed in pixels per second. The conversion can be done afterward, but cannot correct for inaccuracies due to camera misalignment, etc. Both software types can calibrate. The commercial calibration is more in-depth and requires the use of experimental devices that facilitate calibration. The open-source software generally uses a constant multiple that can be chosen by the user, and requires no additional devices.

Quality of Results

The quality of results criteria is based on quality of the processed data, accuracy of data, and the accuracy of the flow field depiction. The quality of the data is a consideration of how presentable data are. The accuracy of the data is dependent on the flow fields being measured; however, intuition will provide a basis to compare the "realness" of the data. The flow field depiction must also be accurate which means that the flow field shown should be represented correctly.

After processing the data, the open-source and commercial software create images that can be accessed that show the flow field characteristics and qualities. Using a specific calibration factor for both of the data sets, the values for the velocities were within five percent of either values. The flow fields generated were similar as well. Despite the small differences in calculated velocities and flow field depiction, the commercial software provides a higher data resolution. Furthermore, there are extraneous vectors present in the open-source software that are smoothed by commercial software.

CHAPTER 4

CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

Based on this evaluation, a Pugh evaluation table (shown below) was used to provide a quantitative basis for the following conclusions. As mentioned in Chapter 2, the commercial software is used as the baseline.

Table 1. Software Pugh Evaluation

Evaluation Criteria	**DaVis**	**OpenPIV**
User Interface		
Ease of Navigation	DATUM	-
Ease of Use	DATUM	-
Error Tolerance	DATUM	-
Software Capabilities		
Image Importing	DATUM	-
Image Preprocessing	DATUM	-
Processing Speed	DATUM	+
Calibration Ability	DATUM	S
Results		
Quality of Processed Data	DATUM	-
Accuracy of Data Values	DATUM	S
Accuracy of Flow Field Depiction	DATUM	S
Total of (+)	0	1
Total of (-)	0	5
Total of (S)	9	3
TOTAL	0	-4

The commercial software shows itself to be a better choice qualitatively than the open-source software. One feature that was not considered was the cost of the software, where open-source software are free, and the commercial software are generally costly. It is important to note that despite the limited efficacy, the use of open-source software as a “quick and dirty” approach is not out of line. Because of the faster processing speed and data accuracy, the software can be used to process images quickly.

Furthermore, there is a clear trade-off between the two software, and thus, it is important to consider the existing data processing infrastructure. Thus far, the Combustion lab has capabilities that support data exported from commercial software. With this consideration, the commercial software becomes more desirable than open-source software which would require the development of new processes.

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