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EFFECTIVE VISUALIZATION OF HEAT TRANSFER

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ABSTRACT

We present a visual analysis and exploration of the transfer of heat via fluid flow through a cooling jacket. Engineers invest a large amount of time and serious effort to optimize the flow through this engine component because of its important role in transferring heat away from the engine block. In this study we examine the design goals that engineers apply in order to construct an ideal-as-possible cooling jacket geometry and use a broad range of visualization tools in order to analyze, explore, and present the visualization of heat transfer. We systematically employ direct, geometric, and texture-based flow visualization techniques as well as automatic feature extraction and interactive feature-based methodology–all from the field of visual computing. We discuss the relative advantages and disadvantages of these approaches as well as the challenges, both technical and perceptual with this application. The result is a feature-rich state-of-the-art flow visualization analysis applied to an important and complex data set from real-world computational fluid dynamics simulations.

1 INTRODUCTION

The department of Advanced Simulation Technologies (AST) at AVL (`www.avl.com`) makes daily use of computational fluid dynamics (CFD) software in order to analyze, explore, and present the results of their simulations. CFD simulation software is used not only to recommend improvements in design of automotive components but also to highlight the cause(s) of engine failure in some cases. In general, one of the major causes of engine failure can result from over-heating.

We present a visual analysis, exploration, and presentation of a feature-rich range of flow visualization methodology in order to investigate and evaluate the design of a cooling jacket from an automotive engine. The goal of fluid in the cooling jacket is to transfer heat away from the engine block as efficiently as possible. The engineers at AVL-AST invest a large amount of time and effort into trouble-shooting and optimizing cooling jacket design because cooling jackets play an important role in engine performance. Our study includes the systematic application of a broad range of approaches including direct, geometric, texture-based, and feature-based e.g., automatic, semi-automatic, and interactive, feature extraction techniques. Each is used to investigate and evaluate the design of a cooling jacket. By systematic we mean, the employment of algorithms all to the same data set and all toward a common goal, namely, the visualization of fluid flow through this important engine component. We discuss the relative advantages

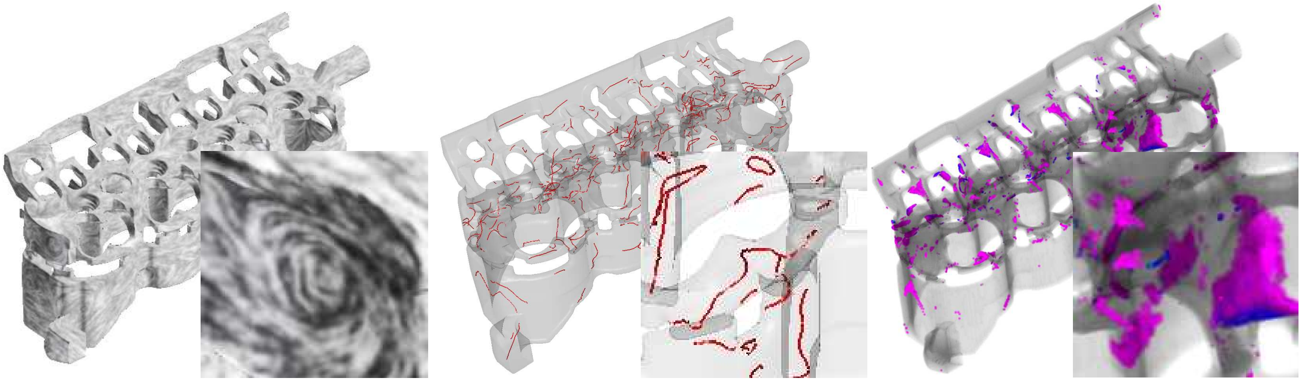

Fig. 1 The visualization of CFD simulation data from a cooling jacket: (left) texture-based flow visualization applied to the surface, (middle) semi-automatic extraction and visualization of vortex core lines using the moving cutting plane method [20] and, (right) a feature-based, focus+context visualization showing regions of near-stagnant flow, specified interactively. Each snap-shot is accompanied by a close-up. This work was the result of a collaboration between visualization researchers and mechanical engineers [11].

and disadvantages of these techniques and give recommendations as to where they are best applied in order to investigate and explore cooling jacket design.

Cooling Jacket Design: The complex shape of the cooling jacket is influenced by multiple factors including the shape of the engine block and optimal temperature at which the engine runs. A very large cooling jacket would be effective in transporting heat away from the cylinders, however, too large of a geometry results in extra weight to be transported. Also, engineers would like the engine to reach its optimal operating temperature quickly. In the following, we describe the major components of the geometry and the design goals of the mechanical engineers responsible for the analysis.

The cooling jacket geometry consists mainly of three components: the cylinder head which is the top, the bottom called the cylinder block, and a thin component connecting the cylinder head and block called the gasket. These three main components are shown pulled apart in Figure 2 for illustration. The cylinder head (top) is responsible for transferring heat away from the intake and exhaust ports at the top of the engine block. The cylinder block is responsible for heat transfer from the engine cylinders and for even distribution of flow to the head. This cooling jacket is used with a four cylinder engine block. Between the cylinder head and block lies the cooling jacket gasket, depicted in Figure 2 as small red ellipses, the actual location of which is revealed by red holes at the top of the cylinder block. The gasket consists of a series of small holes that act as conduits between the block and head. These ducts can be quite small relative to the overall geometry but nonetheless are very important because they are used to govern the motion of fluid flow through the cooling jacket as described in the next section.

Design Goals: There are two main components to the flow through a cooling jacket: a *longitudinal* motion lengthwise along the geometry and a *transversal* motion from cylinder block to head and from the intake to the exhaust side. These two components are sketched in Figure 2. The location of the inlet and outlet are also indicated. Four main design goals are essential for the mechanical engineers: (1) to obtain an even distribution of flow to each engine cylinder, (2) to avoid regions of stagnant flow, (3) to avoid very high velocity flow, and (4) to minimize the fluid pressure loss between the inlet and the outlet

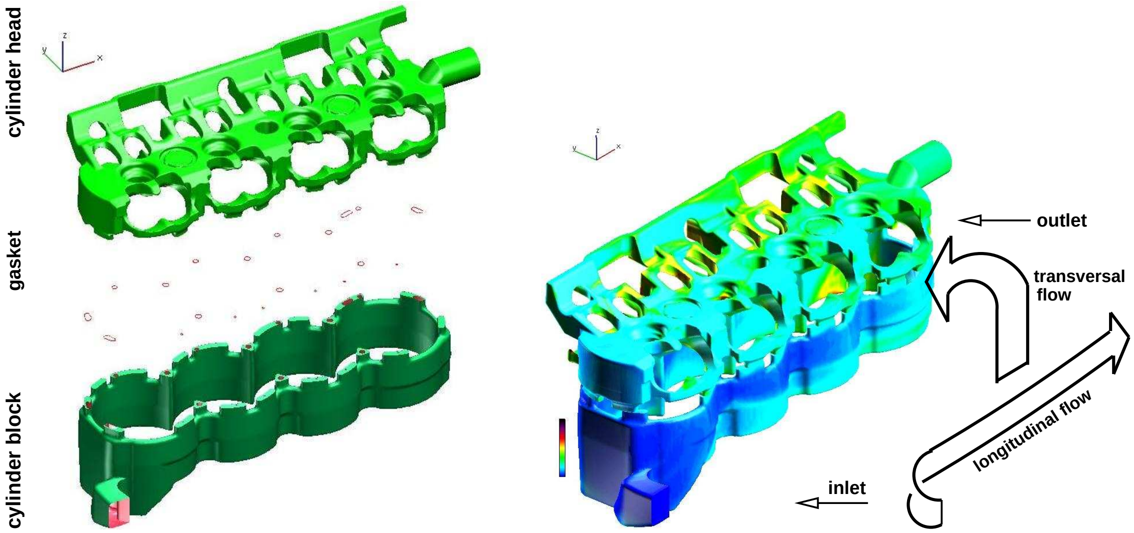

Fig. 2 The cooling jacket has been split apart for illustration. The geometry consists of three primary components: (top) the cylinder head, (middle) the gasket, and (bottom) the cylinder block. (right) The major components of the flow through a cooling jacket include a longitudinal component, lengthwise along the geometry and a transversal component in the upward-and-over direction. The inlet and outlet of the cooling jacket are also indicated. Color is also mapped to temperature in this example.

The first design goal, an even distribution of fluid to each cylinder, is intuitive. An even distribution of flow should result in an even rate of heat transfer away from each cylinder, intake port, and exhaust port. The second goal, avoiding regions of stagnant flow is very important. Stagnant flow does not transport heat away and can lead to boiling conditions. Boiling fluid can indicate potential problem areas in the cooling jacket geometry that lead ultimately to overheating. We note that the optimal cooling jacket temperature is about $90°C$ or $363°K$.

The third goal, to avoid regions of velocity too high in magnitude is less obvious. High velocity flow can lead to *cavitation*–the formation of low-pressure bubbles, such as those resulting from the rotation of a marine propeller. Firstly, cavitation wastes energy in the form of noise. Secondly, cavitation can also lead to damage to the walls of the cooling jacket itself over the long term. Cavitation is associated with explosions and unnecessary vibration. Erosion of the boundary surfaces can result in a shorter product lifetime.

The fourth design goal is to minimize pressure loss across the cooling jacket geometry. The water pump (not shown) located at the cooling jacket's inlet is responsible for maintaining a specified pressure at the inlet. The greater the pressure drop between the cooling jacket's inlet and outlet, the more energy the water pump requires in order to maintain the desired pressure. An ideally straight pipe with an inlet and outlet of equal size would exhibit no pressure loss across its geometry, thus a water pump would require much less energy in this case. Generally, the smaller the cooling jacket gasket, the larger the pressure loss. Curves in the geometry can also cause pressure losses.

The main variable in cooling jacket design lies in the gasket. Engineers adjust the number, location, and size of the conduits (Figure 2, middle) in their pursuit of the ideal fluid motion.

Simulation Data The grid geometry consists of over 1.5 million unstructured, adaptive resolution tetrahedra, hexahedra, pyramids, and prism cells. We also focus on steady flow data for this case because for the cooling jacket, engineers are most interested in investigating the behavior of fluid flow after the simulation has reached a stable state. The fluid in the cooling jacket should reach its optimal temperature rapidly and then ideally remain in this state.

The rest of the paper and its contributions are organized as follows: Section 2 describes our classification of flow visualization techniques and highlights important application related research. Section 3 systematically investigates properties of the flow using direct, e.g. color-mapping, texture-based, e.g., image space advection and dye injection, and geometric flow visualization approaches including streamlines, streamsurfaces, and animated particles. Sections 4 and 5 apply automatic, semi-automatic, and interactive feature-based flow visualization techniques like topology extraction, vortex identification, focus+context (F+C) rendering, and information visualization in order to help us explore, analyze, and evaluate the cooling jacket design. Section 6 presents a discussion, weighs some relative advantages and disadvantages of the respective methods and offers our overall perspectives. Finally Section 7 outlines our conclusions.

2 RELATED WORK AND CLASSIFICATION OF FLOW VISUALIZATION TECHNIQUES

We classify flow visualization techniques into four different groups: direct, texture-based, geometric, and feature-based. For more details on the classification, see our recent state-of-the-art report [12].

In this paper we use an advection approach according to Image Space Advection (ISA) [13]. Scheuermann et al. [18] introduced a method by which to add the normal component of 2D flow to LIC and applied it to visualize the deformation of an intake manifold. Lagrangian-Eulerian Advection was applied in order to visualize vertical motion in ocean flow by Grant et al. [7].

Bauer et al. [1] applied a particle seeding scheme in order to visualize a rotating helical structure in the draft tube of a water turbine. We note that this could also be classified in the feature-based category. Sadlo et al. [17] extended the image-guided streamline placement algorithm of Turk and Banks [21] in order to seed vorticity field lines. Laramee et al. [14] used direct, texture-based, and geometric flow techniques (without feature-extraction methods) to explore swirl and tumble motion, two important in-cylinder flow motions.

Here, we apply both automatic feature-extraction techniques like finding the positions of vector field singularities, vortices, and vortex core extraction [5, 6] and interactive feature-extraction techniques such as those that incorporate information visualization views [3]. Kenwright and Haimes used the eigenvector method for vortex identification to applications in aerodynamics [10]. Sadarjoen et al. apply automatic vortex detection techniques to hydrodynamic flows [16]. Tricoche et al. [20] visualize vortex breakdown using moving cutting planes and direct volume rendering. Doleisch et al. [4] used interactive feature-based flow visualization techniques to track soot in a diesel exhaust system. Post et al. [15] cover feature-based flow visualization in detail.

We apply a feature-rich range of tools from different classes of flow visualization techniques in order to explore and evaluate the design of a cooling jacket.

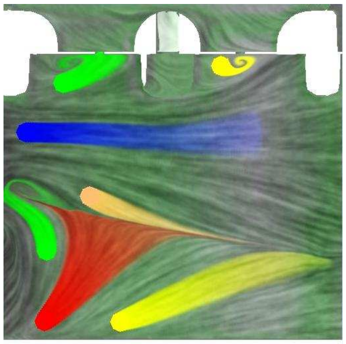

Fig. 3 A close-up view of dye injection used to visualize longitudinal flow at the surface of the cylinder block (intake side) and recirculation zones below the gasket conduits.

3 TEXTURE-BASED, AND GEOMETRIC VISUAL ANALYSIS AND EXPLORATION

This section describes how we applied image-space advection (ISA), dye injection, streamlines, streamsurfaces, and particles to investigate the cooling jacket flow.

Identifying Recirculation with Texture-Based Visualization: Unilateral flow is preferable to recirculating flow because it is more effective in heat transport. We applied ISA [13] to the cooling jacket to gain a complete depiction of the flow at the surface in Figure 1, left. We chose a gray-scale surface color due to perceptual problems when applying both color-mapping and texturing at the same time. Such a combination results in imagery that is overly complex visually, e.g., many small overlapping components of different colors make depth perception more difficult. It is important to note that the opacity of the surface is arbitrary and thus user-defined in our implementation. The user may simply increase the surface opacity to increase depth perception. Also, given the intricate and complex geometry, we prefer not to rely on a technique that requires a parameterization of the surface. We can then zoom in on a subset of the surface in order to gain more detailed insight into the characteristics of the flow. Our texture-based approach gives complete coverage of the vector field and can visualize areas of recirculation. Recirculation can then be highlighted with dye. Figure 3 shows the dye injection applied on top of the ISA texture on the intake side of the cylinder block. The dye helps us discover features like separatrices like the one highlighted between the red, orange-beige, and yellow dye sources. Also highlighted are the small recirculation zones below two of the gasket conduits.

Visualizing Flow Distribution with Geometric Visualization: One of the design goals is an even distribution of flow to each engine cylinder. Streamlines are a geometric approach that can be used used to visualize both longitudinal and transversal behavior of the flow on the exhaust side of the cylinder block. The streamlines can be seeded with a rake and color-mapped with pressure. Although an even distribution is not clear using streamlines, the streamline color-map can reveal a sudden, undesirable pressure drop as flow passes through the gasket conduits. The gasket causes the largest pressure drop between the inlet and the outlet–working against one of the design goals from Section 1. Interactive seeding is tedious given this thin, inter-connected geometry. It can also slow down to less than interactive rates, especially before caching takes place. However, it may be possible to speed up the seeding with hardware acceleration techniques. This is one reason we apply the automatic feature extraction techniques in Section 4.

While streamlines manage to convey an accurate picture of some basic characteristics of the flow, they present challenges in our analysis of this complex CFD dataset for two main reasons: first, they require an

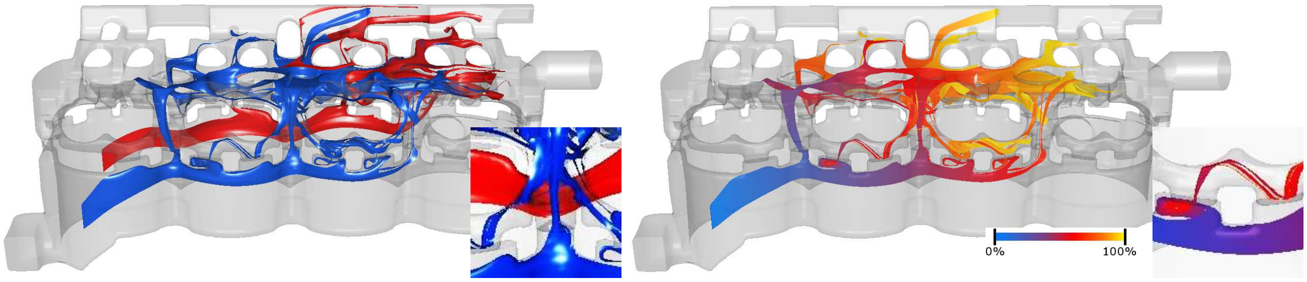

Fig. 4 Streamsurfaces in the cooling jacket: (left) red and blue streamsurfaces are seeded close to the inlet and traverse the jacket mainly in longitudinal direction; (right) parts of a stream surface (color represents time) are pulled into the interconnections and create vortices upon entering the jacket head (highlighted with insets).

appropriate seeding strategy, and second, they can lead to perceptual problems such as visual cluttering if applied en masse. One way in which we address both the seeding and perceptual issues is to use a simple particle seeding scheme similar to that of Bauer et al. [1]. Massless flow particles are generated at the inlet of the cooling jacket and then travel along integral curves through the vector field until they hit a boundary or leave through the outlet. The particles minimize visual clutter and complexity since they do not leave trails as they pass through the complex pathways of the geometry. The individual particles are visualized by an animation of simple point primitives, with optional color mapping of flow attributes. Despite the relative simplicity of this approach, it is very effective in identifying regions where the flow is undesirably slow or nearly stagnating especially in an animation. [1] Furthermore, the dynamics of the particle movement serves to clarify the overall flow behavior stemming from the inlet, since velocity is implicitly contained in the visualization either through the speed at which the particle travels or through color-coding.

Streamsurfaces are another approach we employed to address the visual problems of streamlines in the analysis of the complex flow patterns in the cooling jacket geometry. Following the approach of Garth et al. [5], streamsurfaces are computed by an enhanced version of Hultquist's algorithm [8]. Figure 4 shows two streamsurfaces originating in the block surrounding the first cylinder. Both streamsurfaces show laminar behavior at the start, however, parts of either surface are drawn into the gasket joining the cylinder block and the head and continue from there to the outlet. It is clearly visible how the mostly laminar flow in the head is disrupted by the flow entering the head through the gasket, creating vortices in the flow through the head (see Figure 4). The effect of the gasket on the flow structure is shown as a result. As with most geometric flow visualization techniques, color mapping of flow attributes can be applied to make use of the role of streamsurfaces as natural flow probes. Both streamsurfaces were seeded interactively as a result of the complicated jacket geometry. Furthermore, we were unable to use boundary topology as a means of seeding (see Section 4). Like streamlines, seeding streamsurfaces that provide insight can be tedious. We also experimented, less successfully, with isosurfaces which yielded complex, disconnected imagery with less insight. Hence we also employed the feature-extraction techniques in Sections 4 and 5.

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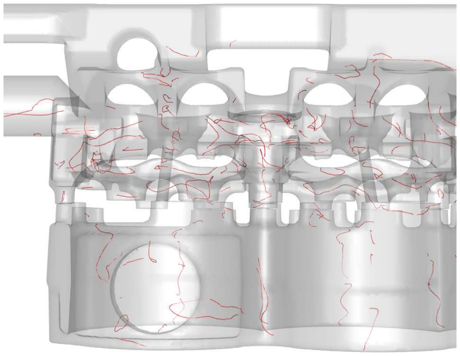
[1] For supplementary, high resolution images and animations including a full length video, please visit `http://www.VRVis.at/scivis/laramee/jacket/`



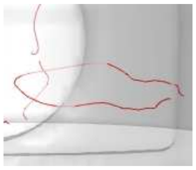


Fig. 5 Results of the Sujudi-Haimes vortex core line extraction method, (inset) a torus shaped vortex core.

4 AUTOMATIC, FEATURE-EXTRACTION AND TOPOLOGY-BASED METHODS

Vortices and vortex cores are not part of the ideal pattern of motion depicted in Figure 2. This section describes the results of applying methods that automatically or semi-automatically extract topological information and vortex core lines.

3D and Boundary Topology: Among the automatic feature-based techniques, topological methods take a prominent role. For simple datasets, or datasets with a high degree of symmetry, these methods usually provide insightful visualization results by depicting the flow's structural skeleton by means of critical points in the flow field and connecting separatrices or separation surfaces. However, for complex 3D flows, satisfying solutions are still elusive, especially in the case of unstructured, adaptive resolution meshes like the cooling jacket.

As in the 3D case, we were unable to obtain visualizations of boundary topology free of perceptual problems, again due to the very high number of critical points (hundreds). Numerical treatment here is further complicated by the fact that not only must the dataset be resampled, but constructing a good tangent space representation of the vector field at the surface in order to compute separatrices is especially difficult. These challenges as well as the high number of critical points provide strong motivation for alternative solutions such as dynamic cutting plane topology (below) and the F+C methodology we describe in Section 5.

Vortex Core Line Extraction: Vortices are interesting features of the cooling jacket design insofar as they can have both desirable (mixing of hot and cold constituents of the flow) and harmful effects (increased overall flow resistance) in this setting. The moving cutting-plane scheme discussed above does not detect all vortices in a dataset, because vortices with a transversal axis are generally not detected by the method. To gain a more complete picture, we have applied the method of Sujudi and Haimes [19]. Care must be taken in the computation of the resulting core lines due to the derivatives involved. However, after careful filtering of the dataset and the algorithm results we were able to produce an insightful visualization. The vortex core lines are rendered illuminated for spatial perception (Figure 4). We also experimented with the λ_2 method [9] but did not find it provided additional insight to what has already been presented.

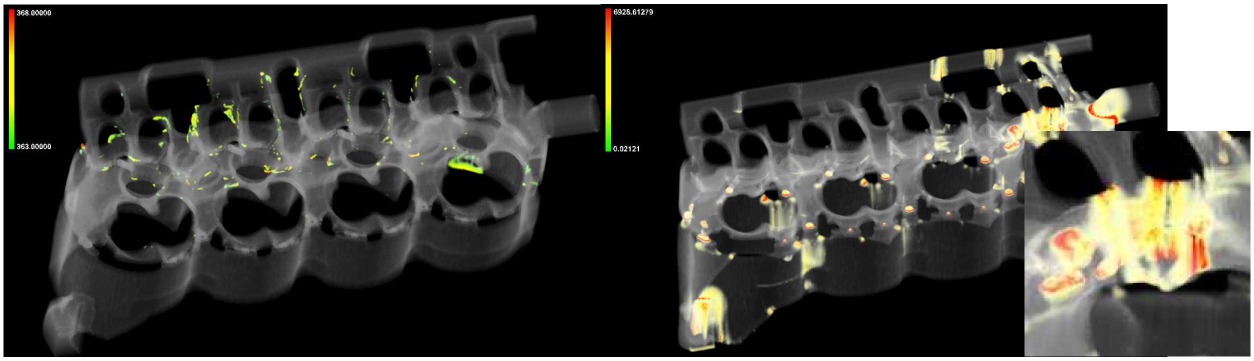


Fig. 6 (left) Areas of temperature $t \geq 363°K$ are interactively-specified by the user and rendered in focus. (right) The regions of very high pressure gradient, (inset) an unexpected high pressure gradient.

5 INTERACTIVE, FEATURE-BASED TECHNIQUES

We also employed state-of-the art feature-based visualization techniques that allow the user to specify a region(s) of interest interactively [3, 4]. The regions are then rendered as the focus in a focus-plus-context (F+C) visualization style.

Extracting Regions of Stagnant Flow: Figure 1, right, illustrates a region of interest with a velocity value, **v**, of less than 0.1 m/s, more specifically: $|\mathbf{v}| < 0.1m/s$. We know that regions of stagnant flow, like those in Figure 1, right, are less effective in transporting heat away from the engine. Our interactive feature-specification environment is also effective for the multi-attribute data analyzed in this study. The color-coding in Figure 1 right indicates temperature. The optimal fluid temperature, $363°K$ is mapped to magenta and high temperature is mapped to blue. This visualization result indicates that there are very few, small regions where low velocity and high temperature coincide–an advantageous design characteristic.

Figure 6 further refines the feature specification, by restricting the focus to include only high temperature values. The new feature is defined using **v** and temperature, t as:

$$(|\mathbf{v}| < 0.1m/s) \cap (364°K < t)$$

The result in Figure 6 is a less cluttered image, showing undesirable regions, where slow flow and hot flow are apparent. These regions are less effective in transporting heat away. Fortunately, these regions seem to be rather small, thus, from a heat-transfer point of view, the simulation results point toward a good design. Areas of very high velocity, leading to cavitation, can be identified in a similar way. Recall, avoiding high velocity magnitude was a goal outlined in Section 1.

Extracting Reverse-Longitudinal Flow: Figure 7 depicts the result of selecting all negative X-velocity values via brushing. The positive X-velocity component is aligned with the longitudinal flow direction. Thus all regions containing a negative X-velocity component are flowing, at least partially, backward instead of traversing the shortest path from inlet to outlet. This extracted feature may also point out recirculation zones. We can further refine the region of interest by including only velocity values with negative X *and* negative Z components. Figure 7, right, depicts the regions where flow

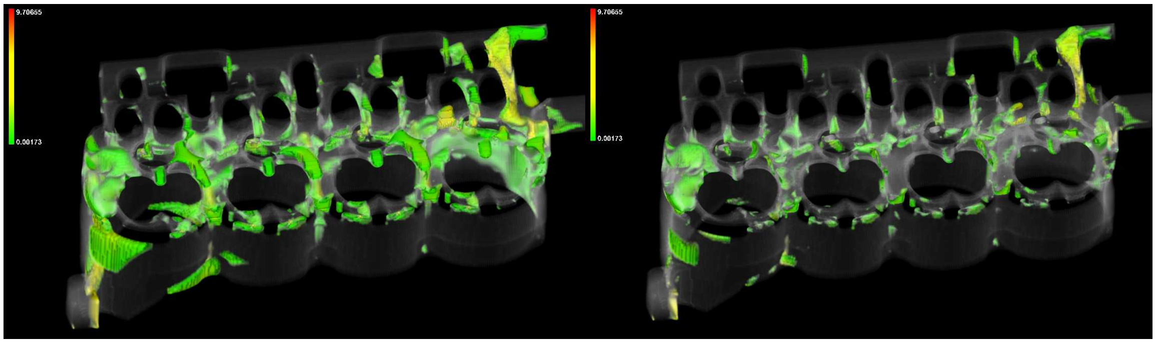


Fig. 7 (left) The visualization identifying all regions of reverse longitudinal flow. Color-mapping reflects velocity magnitude. (right) The result identifying all regions of reverse longitudinal flow and regions of reverse-transversal flow.

moves backward (reverse-longitudinal) and down (reverse-transversal) instead of the shortest path–up and forward from inlet to outlet. From this result, we can deduce that flow through the cylinder head is a complex patchwork of flow, especially along the center of the head.

The interactive feature-specification uses multiple, linked views to define features. Any scientific view, like that shown in Figures 6 or 7, can be linked with a range of different information visualization views. We used a scatter plot and brushing tool to identify the combination of reverse-longitudinal and reverse-transversal flow. The feature specification was done interactively using brushing to encircle the data values of interest.

Regions of High Pressure Gradient: As part of our investigation of the cooling jacket data set we have implemented the ability to compute scalar derivative information. We can now extract derivative information for the pressure simulation attribute and use it to identify the areas of the cooling jacket geometry with the largest pressure drop. These are the areas that draw the most energy from the water pump. We also know from experience that areas of pressure drop are associated with areas of high velocity flow.

Figure 6 shows the regions of large pressure gradient, (gradient, $g > 5,550 Pa$). We notice the large pressure drop expected through the gasket conduits. However, unexpectedly, we see large pressure gradients near both the inlet and the outlet as well other areas. These are areas that can be brought attention to the engineer for future optimization.

6 DISCUSSION

Note that we made very limited use of 2D slices in our investigation. Slices are of very limited use in this case because the thin geometry has such a high surface area. Slicing can result in small disconnected components that are more difficult to interpret, like the slice shown in Figure 2, middle used to illustrate the gasket. The complex nature of this particular case also ruled out the use of any surface parameterization. This is one reason our texture-based flow visualization at the surface was useful. Other reasons are that it is fast and avoids the seeding problem by providing complete coverage. Areas of recirculation at the surface are animated and the user can zoom in to an arbitrary level of detail.

Despite the helpful visualization result of the automatic feature-extraction approaches, the problems we encountered with the application of topological methods in our context show that there is still work to be done in order to accommodate a wider selection of modern datasets. As a fully automatic feature extraction scheme, flow topology is still very appealing. Needed are automatic extraction methods that allow reduction in visual complexity and identify more elements of 3D flow fields associated with unstructured, adaptive resolution grids.

The F+C visualization has proven very useful in our analysis of the cooling jacket for two important reasons: (1) the volume rendered result allows the user to see through the intricate components of the geometry preventing areas deemed unimportant from occluding the region of interest and (2) interactive thresholding gives the user the opportunity to reduce the enormous complexity of some of the cooling jacket's flow behavior and resulting visualization. In other words, the user is afforded an arbitrarily narrow focus. Linking the scientific view with the information visualization view is an essential part of the focusing process.

7 CONCLUSIONS AND FUTURE WORK

We have applied a feature-rich range of state-of-the-art feature-extraction and visualization techniques in order to investigate the flow of fluid through a cooling jacket. Our features included texture-based approaches like image space advection and dye injection, geometric tools including streamlines, streamsurfaces, and particles, automatic, topology-based feature-extraction algorithms, and interactive feature-based strategies incorporating F+C rendering and linked information visualization views.

Future work could take on multiple directions including the development of more robust automatic, surface-based, feature-extraction techniques and also the application of arbitrary filters to topological features. For example, the application of the pair-distance filter described by De Leeuw and Van Liere [2] to the results described in Section 4 could prove to be very useful.

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