Data Visualization, Proceedings of the Joint EUROGRAPHICS - IEEE VGTC Symposium on Visualization (EuroVis 2006)

Conference contribution :

Laramee, B. (2006). *Texture Advection on Stream Surfaces: A Novel Hybrid Visualization Applied to CFD Simulation Results.* Data Visualization, Proceedings of the Joint EUROGRAPHICS - IEEE VGTC Symposium on Visualization (EuroVis 2006),

http://dx.doi.org/http://dx.doi.org/10.2312/VisSym/EuroVis06/155-162

Eurographics/ IEEE-VGTC Symposium on Visualization (2006)
Thomas Ertl, Ken Joy, and Beatriz Santos (Editors)

Texture Advection on Stream Surfaces: A Novel Hybrid Visualization Applied to CFD Simulation Results

Robert S. Laramee,[1] Christoph Garth,[2] Jürgen Schneider,[3] and Helwig Hauser[1]

[1]The VRVis Research Center, Vienna, Austria, email: {Laramee,Hauser}@VRVis.at
[2]Department of Computer Science, University of Kaiserslautern, Germany, e-mail: garth@informatik.uni-kl.de
[3]Department of Advanced Simulation Technologies, AVL, Austria, e-mail: juergen.schneider@avl.com

Abstract

Stream surfaces are a classic flow visualization technique used to portray the characteristics of vector fields, and texture advection research has made rapid advances in recent years. We present a novel hybrid visualization of texture advection on stream surfaces. This approach conveys properties of the vector field that stream surfaces alone cannot. We apply the visualization technique to various patterns of flow from CFD data important to automotive engine simulation including two patterns of in-cylinder flow (swirl and tumble motion) as well as flow through a cooling jacket. In addition, we explore multiple vector fields defined at the stream surface such as velocity, vorticity, and pressure gradient. The results of our investigation highlight both the strengths and limitations of the hybrid stream surface-texture advection visualization technique and offer new insight to engineers exploring and analyzing their simulations.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation; I.3.7 [Computer Graphics] Three-Dimensional Graphics and Realism–Color, shading, shadowing, and texture; [Simulation and Modeling]: Simulation Output Analysis

1. Introduction

Stream surfaces, introduced by Hultquist [Hul90, Hul92], are a well known technique used to visualize properties of flows. They can circumvent the visual complexity or clutter associated with seeding many streamlines. With stream surfaces alone, it is difficult to unambiguously convey the downstream and upstream directions of the flow. Texture advection is another effective flow visualization technique that transports texture properties in the direction of the flow in an animated sequence. Texture advection techniques [JEH02, LvWJH04, WHE01, WEHE02] offer the advantages of being fast and providing complete coverage of the vector field domain.

We present a hybrid visualization which combines the strengths of both stream surfaces and texture advection techniques. The insight provided by traditional stream surfaces is enhanced with fast texture advection on the surface that conveys the direction of the flow through the use of animated convolution of noise textures. By adding a complementary texture-based algorithm we also capture complete coverage of the flow domain across the stream surface. The hybrid visualization is then used to investigate three important patterns of flow found in engine simulation data: swirl and tumble motion typical of in-cylinder flow and fluid flow through a cooling jacket. The visual analysis and exploration of the engine simulation data is driven by design goals from an engineering point of view. Applying texture advection to stream surfaces raises both technical and perceptual challenges which we address here. The results of our study highlight both the advantages and limitations of the hybrid visualization approach and provide new insight to those engineers investigating the properties of the automotive components they are analyzing.

The rest of this paper is organized as follows: Section 2 presents past research related to both stream surface generation and texture advection approaches on general surfaces. Our hybrid method is presented in Section 3 including an investigation of the in-cylinder patterns of motion (Section 3.2) and flow through a cooling jacket (Section 3.3). Both perceptual and technical challenges associated with the hybrid visualization are addressed as well as the insight gained by the engineer from the visualization. A discussion of the results and conclusions are discussed in Sections 4 and 5 respectively.

2. Related Work

Our review of research literature focuses on previous work related to stream surface computation and texture-advection on surfaces.

Stream Surfaces: Stream surfaces were introduced to the visualization community by Hultquist [Hul90, Hul92]. An implicit stream surface algorithm was presented by Van Wijk [vW93] based on the observation that streamsurfaces could be computed starting along 2D isolines at the domain boundary. Scheuermann et al. [SBH*01] adapted the stream surface computation to tetrahedral grids. More recently, Garth et el. [GTS*04] describe a stream surface computation that delivers accurate results in regions of intricate flow, e.g., in vortex regions.

Texture Advection on Boundary Surfaces: The amount of research in the area of texture advection on surfaces is relatively small. Two texture advection algorithms on surfaces were introduced in 2003: Image Space Advection (ISA) [LJH03] and Image Based Flow Visualization for Curved Surfaces (IBFVS) [vW03]. A comparison of the two algorithms is described by Laramee et al. [LvWJH04]. Weiskopf and Ertl [WE04] present research that exploits GPU programming for fast texture-based flow visualization on surfaces. Each of these previous research results focus on flow at the boundary surface.

Texture Advection on Isosurfaces: Although flow visualization at the boundary surface is very useful, clearly engineers are interested in visualizing flow inside the boundary of the domain. Slices are common but cannot always successfully portray intrinsic 3D characteristics of the flow. Texture-advection was also applied to isosurfaces [LSH04]. The major drawback to this approach lies in cognition of the results. If we compute an isosurface, say, of velocity magnitude, we do gain insight into the inherent 3D structure of the flow. However, portions of the isosurface have a strong normal component to the flow orthogonal to the surface itself. As soon as we advect texture properties along the isosurface to reflect the downstream and upstream directions of the flow, the visualization can be considered misleading, especially if this normal component of the flow is not taken into account. This is one central motivation for investigating texture-advection on stream surfaces. Stream surfaces are aligned with the flow by definition and animating texture properties in the direction of the flow is intuitive when interpreting the visualization. Furthermore, from a technical point of view, the vector field in this case does not require projection onto the surface since it is aligned with the stream surface by definition. This vector field projection phase is necessary for the implementation on boundary and isosurfaces. This topic is elaborated on in Section 3.2.

We note that another attempt has been made at visualizing the downstream direction of the flow on stream surfaces by Löffelmann et al. [LMG97]. They cut away explicit arrow-shaped portions of the stream surface which indicate the direction of the flow. The disadvantages here are the computation time, the problem of optimal stream arrow placement, and computing the optimal size of each arrow. Löffelmann et al. [LMGP97] also mapped static textures to stream surfaces in order to visualize dynamical systems. The difficulties in this case stem from finding the optimal parameterization of the streamsurface in order to map the 2D textures. Performance time also presents challenges.

3. Texture Advection on Stream Surfaces: Applied to In-Cylinder and Cooling Jacket Flow

Here we describe our choice of stream surface generation and texture advection algorithm and the motivation for those choices. We then investigate three different patterns of engine simulation flow: swirl and tumble motion characteristic of in-cylinder flow and the behavior of fluid flow through a cooling jacket. We'll see what insights can be realized with our hybrid visualization as well as some of its limitations.

3.1. Method Background

For stream surface generation, we chose to implement the algorithm of Garth et al. [GTS*04] for several reasons. It computes accurate results in regions of intricate flow and thus can handle very complicated flow structures. This property proves to be requisite in Section 3.3 when visualizing flow through the cooling jacket. The implementation has also been shown to apply well to unstructured, adaptive resolution grids, a perquisite for each pattern of flow we visualize here (and not characteristic to all streamsurface generation implementations).

For the texture advection algorithm, we implemented and applied ISA [LvWJH04]. ISA has several properties which we require for the applications discussed here. ISA: (1) generates a dense representation of flow on adaptive resolution stream surfaces, (2) visualizes flow on complex stream surfaces composed of polygons whose number is on the order of 500,000 or more, (3) visualizes flow independent of the stream surface mesh complexity and resolution, (4) supports user-interaction such as rotation, translation, and zooming always maintaining a constant, high spatial resolution, (5) does not rely on any parameterization of the surface, and (6) produces fast animations, realizing up to 60 frames per second. We note that IBFVS [LvWJH04] could also have been applied as well as the technique from Weiskopf and Ertl [WE04].

3.2. In-Cylinder Flow: Swirl and Tumble Motion

For flow entering and exiting a combustion chamber, the engineers responsible for the design try to create an ideal pat-

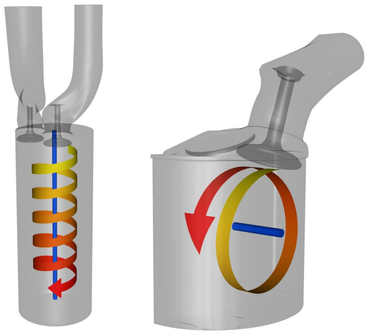

Figure 1: *(left) The swirling motion of flow in the combustion chamber of a diesel engine.* Swirl *is used to describe circulation about the axis aligned with the valve cylinder. The intake ports at the top provide the tangential component of the flow necessary for swirl. The data set consists of 776,000 unstructured, adaptive resolution grid cells. (right) Some in-cylinder flows require a* tumble *motion flow pattern in order to mix fluid with oxygen. Tumble flow circulates around an axis perpendicular to the cylinder axis, orthogonal to the case of swirl motion.*

tern of motion. The motion can be described as a swirling flow revolving around an imaginary, central axis residing inside the cylinder volume. One type of swirling motion, aptly called *swirl motion*, is depicted in Figure 1, left. The ideal swirl motion spirals around an axis aligned with the cylinder volume found at the center. Such an ideal is often strived for in diesel engines.

Another important pattern of flow is *tumble motion*, depicted in Figure 1, right. The axis of rotation in the tumble case is orthogonal to that of the swirl case. Also, the ideal motion is closer to a simple circle rather than a more spiral-like pattern. Since the axis of rotation is not aligned with the combustion chamber itself, this pattern of motion is more difficult to realize.

Achieving these ideal patterns of flow optimizes the mixture of oxygen and fuel during the ignition phase of the valve cycle. Optimal ignition leads to very desirable consequences associated with the combustion process including: more burnt fuel (less wasted fuel), lower emissions, and more output power.

Swirl Motion: Engineers have different options and tools at their disposal when visualizing the flow to see how close it approximates the ideal. Previously, they were limited to a combination of slices and texture-based visualization techniques. This was followed by texture advection on boundary surfaces. Engineers often start their visual analysis by looking at the boundary since it provides an overview. Afterward, they may then investigate the inside volume. One classic tool engineers have to visualize the volume are isosurfaces. Figure 2 left, shows the depiction of swirl motion inside a combustion chamber from a diesel engine simulation using an isosurface. Texture advection can be added to the isosurface in order to portray more detail and further characteristics of the flow on the isosurface, as in Figure 2 middle-left.

Both the velocity isosurface and additional texture advection on the isosurface do provide further information about the three-dimensional characteristics of the flow inside the piston chamber, however, interpretation of the results is difficult. This stems mainly from the fact that the flow is not tangential to the isosurface in many areas. This makes a velocity isosurface itself more difficult to interpret. Texture advection on the isosurface can be considered misleading if the normal component of the flow to the isosurface is not taken into account. A more intuitive approach is to use stream surfaces. Figure 2 middle-right shows a stream surface seeded near one of the intake ports of the geometry. This streamsurface conveys the 3D characteristics of the swirl motion in a very intuitive manner. Figure 2 right shows a novel hybrid visualization of texture advection on the same stream surface. The result shows more characteristics of the flow than a stream surface alone. The viewer can see how the flow aligns with the surface itself. Watching the texture properties flow downstream is especially intuitive during animation [LGSH05]. From an engineering point of view, the simulation results indicate a satisfactory design and simulation. In other words, a nice swirl motion pattern has been achieved here. From an engineering point of view, the design of the model is good and achieves a nearly optimal mixing of fuel and oxygen.

Tumble Motion: Figure 3 shows a stream surface seeded near the intake port of the combustion chamber of a model gas engine cylinder. Color is mapped to velocity magnitude and a candidate tumble axis is annotated. The tumble axis is off-center and not aligned with the ideal tumble motion axis. The axis is slanted downward and to the left. The position of the tumble axis can be seen however the downstream and upstream direction of the flow cannot be inferred unless we use a hybrid visualization as shown in Figure 4. The first image in Figure 4 adds the texturing to the flow field defined at the stream surface. How the flow aligns with the stream surface is clarified and we can observe the texture properties flow downstream in a fast animation [LGSH05]. Also, with the texturing convolved according to the flow field, the vortical nature of the candidate tumble axis is clearer. Depicted is flow swirling around an off-center tumble axis. Furthermore, the perception of this vortex is much clearer with the additional texturing.

In addition to visualizing the flow field at the stream surface, we also experimented with advecting texture properties according to other vector fields including the *vorticity* field. Vorticity is the curl of the velocity, namely, $\nabla \times \mathbf{v}$, and represents the local flow rotation. Some results from this investigation are shown in Figures 4, 9, left (color plate), and 5 where noise texture has been convolved according to vorticity. The color mapping in Figures 4 and 5, bottom is accord-

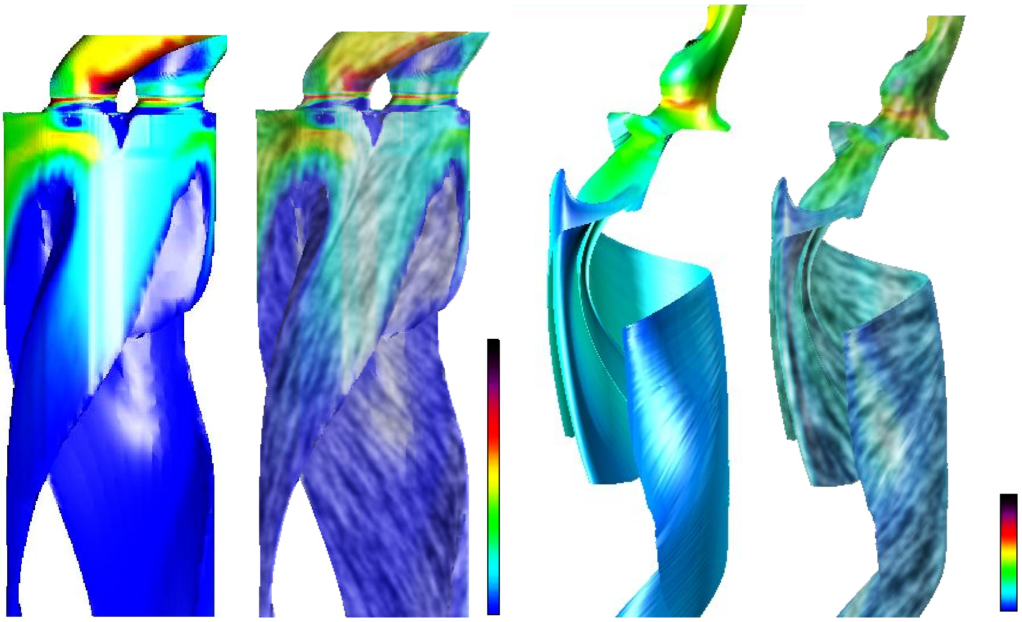

Figure 2: *The depiction of swirl motion with surfaces and texture advection: (left) a velocity isosurface of 5.0 m/s with an addition CFD simulation attribute mapped to hue, (middle-left) a hybrid visualization of texture advection on the same isosurface, (middle-right) a stream surface seeded in an intake port with velocity magnitude mapped to hue, and (right) a hybrid visualization of texture advection on the same stream surface.*

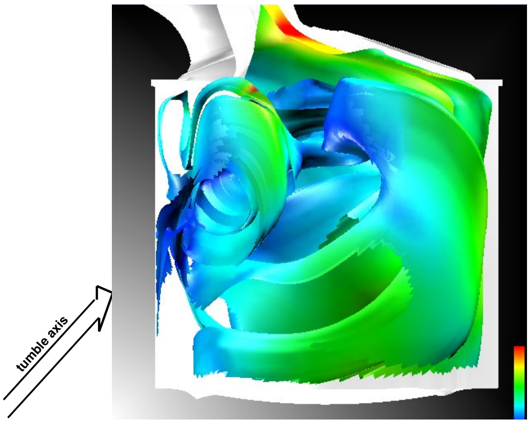

Figure 3: *A stream surface in the gray-scale context of a combustion chamber in a gas engine simulation. A candidate tumble axis is indicated. For the stream surface, color is mapped to velocity magnitude.*

ing to vorticity magnitude. In Figure 9 (color plate), we have implemented an arguably more informative color mapping. Figure 9 shows texture advected according to vorticity and color mapped to *helicity*. Helicity is defined as $\mathbf{v} \cdot (\nabla \times \mathbf{v})$. High helicity values indicate regions where the local velocity and vorticity vectors are nearly parallel, very much reminiscent of the parallel vectors operator [PR99]. Parallel velocity and vorticity may indicate vortex core regions. Figure 9 shows high helicity values in the candidate tumble axis region and in the lower right. The images in Figures 4 and 5 have been positioned in order to facilitate comparisons for the reader. From comparing the vector and vorticity fields, we can observe that vorticity is sometimes orthogonal to the vector field. There also appears to be considerable more fluctuation in the vorticity than the velocity. This is even clearer in an animation [LGSH05] although admittedly, these hybrid results can be visually complex. A discussion of texture advection according to the pressure gradient field is given in Section 4.

Perception: The images in Figure 4 are visually complex. The surfaces are complex to start with and complementing this with texture convolution adds even more. Perceptual problems stem from visual complexity and deciphering different portions of the surface from one another. This is the reason we experimented with different color mappings as shown in Figure 5. Figure 5, top shows the same stream surface and vector fields as Figure 4 but with a different viewing angle and a simplified blue-yellow color mapping. The simplified color mapping can facilitate the perception of both surface and texture properties by reducing visual complexity. According to the findings of Ware [War98, War00], an optimal color sequence varies through a range of colors with each successive hue having a higher luminance than its pre-

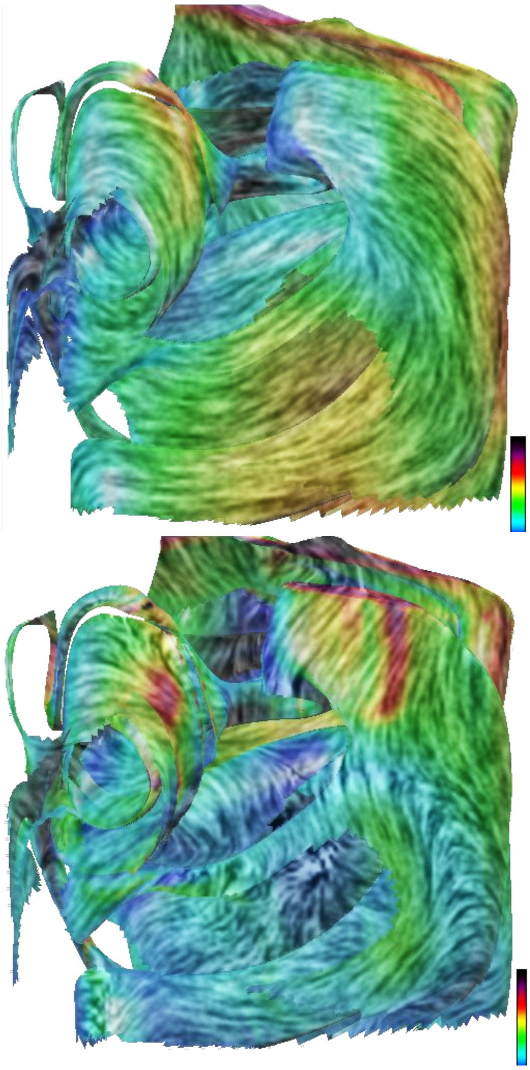

Figure 4: *A hybrid stream surface–texture advection visualization the tumble pattern of motion from the simulation results of a gas engine: (top) velocity magnitude mapped to hue and texture advection applied to the flow field and (bottom) vorticity magnitude mapped to hue and texture advection applied to the vorticity field.*

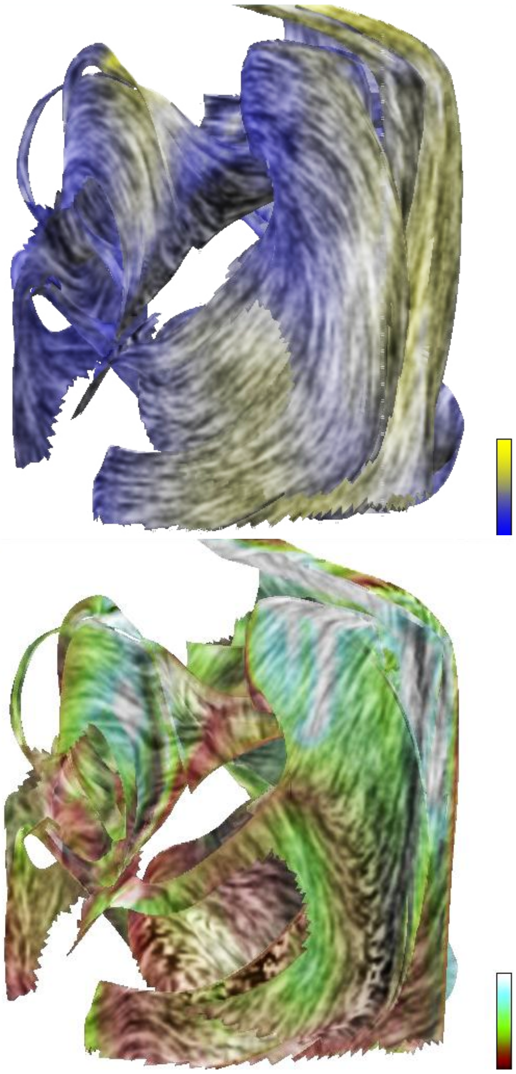

Figure 5: *The same stream surface as shown in Figure 4 viewed from the side and with alternative color mappings: (top) velocity magnitude mapped to a simple yellow-blue color scale and texture advection applied to the flow field, and (bottom) vorticity magnitude mapped to a more optimal color scale and texture advection applied to the vorticity field.*

decessor. Thus, we have experimented with the color map shown in Figure 5, bottom which meets this criterion. User studies indicate that this surface may be easier to perceive than the traditional color mapping used in Figures 3 and 4. Alternative approaches to enhance perception of these surfaces include: mapping color according to depth, e.g., mapping red-scale values in the foreground and blue-scale values toward the background in the manner of Toutin [Tou97] or using fog to emphasize the depth gradient.

We emphasize that although the images shown here are static, the visualizations seen by the engineer are not. Animated texture convolution at real-time frame rates aid the user in perceiving the characteristics of the stream surfaces. Interaction including, zooming, panning, and rotation also play an important role in perception for which there is no substitute. Hence we encourage the reader to view the supplementary video [LGSH05]. We have also implemented a clipping plane for visibility culling.

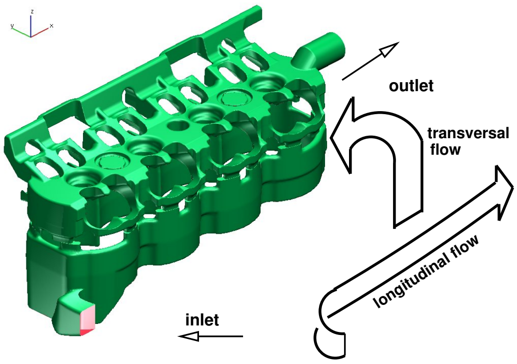

Figure 6: *The major components of the flow through a cooling jacket include a longitudinal component, lengthwise along the geometry and a transversal component in the upward-and-over direction. The inlet and outlet of the cooling jacket are also indicated.*

3.3. Cooling Jacket Flow

The previous applications of in-cylinder flow simulation highlight some of the strengths of a hybrid texture advection–stream surface visualization. While we also gain heightened insight in the case of cooling jacket flow, this application points out some limitations of the approach. We precede our findings with a brief description of the ideal flow through the jacket geometry.

The cooling jacket has an extremely complex geometry. The model grid consists of over 1.5 million unstructured, adaptive resolution tetrahedra, hexahedra, pyramid, and prism volume elements, the size of which differs by more than six orders of magnitude. Our stream surface tessellations are correspondingly complicated, containing over 500,000 polygons in some cases. There are two main components to the ideal pattern of 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 6. The location of the inlet and outlet are also indicated. Any flow that deviates from this ideal, essentially the most efficient volume-filling path from inlet to outlet, results in less transfer of heat away from the engine block.

Stream surface seeding, computation, and visualization can help the engineer understand the behavior of the flow and compare the simulation data with the ideal. Figure 7 shows two stream surfaces seeded in the cylinder block side (lower half) of the jacket's volume near the inlet. The stream surfaces start off highlighting the laminar characteristics of the flow until the flow travels upward in the transversal direction. The flow is drawn into the cylinder head side (top half) of the geometry through small fluid conduits. During this transition from cylinder block to cylinder head (bottom to top) the flow becomes a very complicated patchwork characterized by many vortices. (The depiction of individual vortices can be found in previous literature [LGD*05].)

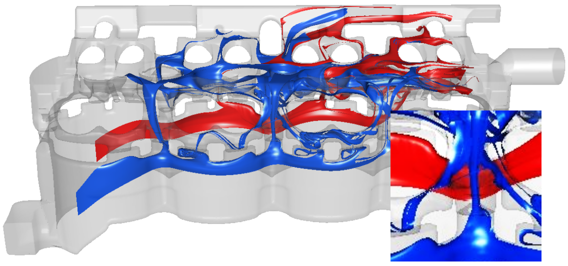

Figure 7: *Streamsurfaces in the cooling jacket: (top) red and blue streamsurfaces are seeded close to the inlet and traverse the jacket mainly in longitudinal direction. Parts of a stream surface are drawn into the interconnections and create vortices upon entering the jacket head (highlighted in inset).*

From our experience and the *a priori* knowledge of the engineers investigating this type of flow, it appears as if the flow is generally traveling in the longitudinal direction in the cylinder block and then the transversal direction as it is drawn into the head. However, it is not until we apply texture-advection to the stream surface that non-ideal portions of the flow are evident.

Figure 8 shows a hybrid texture-based-stream surface visualization using the same stream surface geometry seeded in blue in Figure 7. What becomes clear with the additional texture-advection are patches of flow that deviate from the ideal. This includes recirculation zones and reverse-longitudinal flow–both of which reduce the effectiveness of heat transfer away from the engine block. A recirculation zone is highlighted in Figure 8, lower left, while reverse-longitudinal flow can be observed in both loop stream surface structures in the lower right close-up. This is especially apparent in an animation [LGSH05].

Technical and Perceptual Problems: Some of the challenges in this application stem from technical factors and perception. The sheer complexity of the geometry results in stream surfaces with correspondingly complex shape. The cylinder block and cylinder head (the bottom and top halves) are separated by a gasket component. The gasket component contains a series of very small fluid conduits whose number, position, and size control the distribution of flow to and away the four cylinders. As the stream surface computation traverses from the block to the head, the surfaces must necessarily become very thin. In fact, the stream surfaces start to look more like streamlines. From a technical point of view, this makes the stream surface generation algorithm of Garth et al. [GTS*04] particularly suited to this application because of its ability to navigate through such intricate

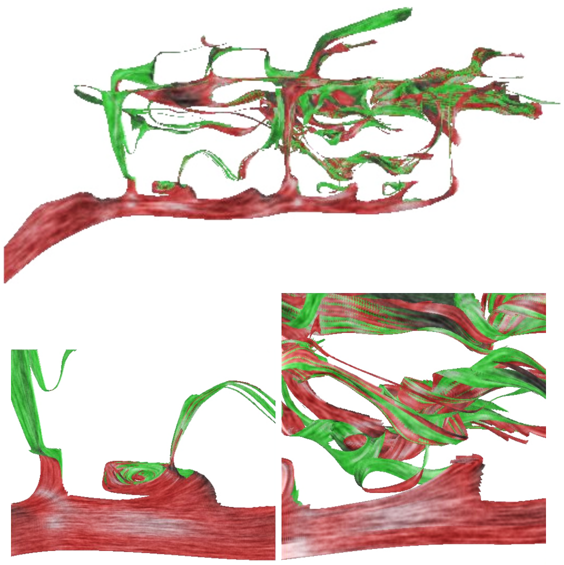

Figure 8: *A hybrid texture advection-stream surface visualization. A color (red and green) is assigned to each side of the stream surface in order to aid perception of the surface properties: (top) The same stream surface shown in Figure 7 is complimented with texture advection: (bottom-left) a close-up of recirculation zone is highlighted and (bottom-right) a close-up view of a region with high vorticity.*

geometry in a robust manner. As a consequence of the gasket conduits, our hybrid visualization may amount to what is essentially texture advection on streamlines. Streamlines do not provide enough spatial coherence for sensible texture advection. Even if the spatial frequency of our convolved noise texture were on the scale of a unit pixel (which was not originally intended), its advection would not be clearly perceivable on a streamline only 1-2 pixels in width. This is both a technical and a visual limitation. To our knowledge, the only way to resolve this is by zooming in on the geometry until a spatially coherent geometry is obtained.

The visual complexity of thinly connected stream surfaces poses perceptual challenges for the viewer just as streamlines do in this same application. One way we address the visual complexity is with a simple color mapping. As illustrated in Figure 8, opposite sides of the stream surface are assigned different colors: one side of the stream surface is red, the other green. As the surface twists and folds over itself it is easier to perceive. This is especially noticeable in areas of high vorticity.

4. Discussion

For higher resolution images and animations, including a full length video, please visit:

http://www.VRVis.at/scivis/laramee/isa-streamsurface/

For each of the visualizations, performance time after stream surface generation is fast: often in real-time. A detailed discussion of texture advection performance times can be found in previous literature [LvWJH04].

We note that stream surface seeding still remains a challenge and is to some extent arbitrary. For all the stream surfaces shown in this paper we used our *a priori* knowledge of the applications, just as an engineer does, during our investigation. Engineers analyzing these simulations are very familiar with the characteristics of their models. In general, the regions near intake ports are an intelligent seeding choice and provide insightful results. However, this does not completely eliminate some trial and error.

On the topic of perception, another issue stems from the surface visibility in conjunction with texture-based vector field visualization. If the noise textures are not adequately transparent, the surface may be more difficult to see. The optimal transparency of texture properties depends on what the viewer is most interested in. That is why we give the user interactive control over the transparency of textures and corresponding surface opacity. The user may decide to increase transparency of the textures in order to see more of the surface or increase the opacity of the texture advection in order to see more of the flow. Implementation details are described elsewhere [LJH03].

In addition to advecting texture properties according to the velocity and vorticity fields at the stream surface, we have also investigated the pressure gradient field. The characteristics of the pressure gradient field at the stream surface, are depicted in Figure 9, right (color plate). Interpretation of the results is difficult. It looks as if the pressure gradient is orthogonal to the boundary geometry, however, further investigation is necessary in order to verify this observation. Also we must use caution when interpreting the visualizations of either the vorticity or pressure gradient fields on a stream surface because these are not always aligned with the stream surface geometry as in the case of the flow field. Nonetheless, our hybrid visualization allows the engineer to explore the relationship between velocity, vorticity, and pressure gradient attribute fields in a novel way.

5. Conclusions and Future Work

We have introduced a novel hybrid visualization of texture advection on stream surfaces. We've applied the technique to three important patterns of flow from automotive simulation. The combination of texture-advection and stream surfaces raises both technical and visual challenges that can be addressed with both interaction and simple but intelligent color mapping choices. We also experimented with advecting textures according to various vector fields defined at the stream surface including flow, vorticity, and pressure gradient fields. The hybrid visualization allows engineers to explore the relationships between these attributes in a way not previously possible. Our investigation shows that texture-advection enhances stream surfaces by depicting properties of the flow that the surfaces alone cannot. In this case, the texture advection points out both ideal and non-ideal subsets of flow motion. The hybrid visualizations also provide a much more detailed depiction of simulation results than stream surfaces alone. Although more visual information provides further insight to those engineers analyzing the simulation results the hybrid visualization does have limitations.

Future work could take on several directions including the computation of of time-dependent stream surfaces. The relationship of stream surfaces with other topological features of the flow also looks to be a fruitful research direction. Computing a texture advection visualization in true 3D (as opposed to surfaces in 3D) continues to be a challenge to researchers. The optimal trade-off between domain coverage and perceptibility promises to be elusive for years to come.

Acknowledgments: The authors thank all those who have contributed to this research including AVL (`www.avl.com`) and Kplus (`www.kplus.at`). We would like to thank the reviewers for their valuable feedback. All CFD simulation data shown in this paper has been provided courtesy of AVL. For readers interested in discussing collaborative research ideas, please contact the first author.

References

[GTS*04] GARTH C., TRICOCHE X., SALZBRUNN T., BOBACH T., SCHEUERMANN G.: Surface Techniques for Vortex Visualization. In *Data Visualization, Proceedings of the 6th Joint IEEE TCVG–EUROGRAPHICS Symposium on Visualization (VisSym 2004)* (May 2004), pp. 155–164.

[Hul90] HULTQUIST J. P. M.: Interactive Numerical Flow Visualization Using Stream Surfaces. *Computing Systems in Engineering 1*, 2-4 (1990), 349–353.

[Hul92] HULTQUIST J. P. M.: Constructing Stream Surfaces in Steady 3D Vector Fields. In *Proceedings IEEE Visualization '92* (1992), pp. 171–178.

[JEH02] JOBARD B., ERLEBACHER G., HUSSAINI Y.: Lagrangian-Eulerian Advection of Noise and Dye Textures for Unsteady Flow Visualization. *IEEE Transactions on Visualization and Computer Graphics 8(3)* (2002), 211–222.

[LGD*05] LARAMEE R. S., GARTH C., DOLEISCH H., SCHNEIDER J., HAUSER H., HAGEN H.: Visual Analysis and Exploration of Fluid Flow in a Cooling Jacket. In *Proceedings IEEE Visualization 2005* (2005), pp. 623–630.

[LGSH05] LARAMEE R. S., GARTH C., SCHNEIDER J., HAUSER H.: Texture Advection on Stream Surfaces–Supplementary Material: High resolution Images and Animations, December 2005. http://www.VRVis.at/scivis/laramee/isa-streamsurface/.

[LJH03] LARAMEE R. S., JOBARD B., HAUSER H.: Image Space Based Visualization of Unsteady Flow on Surfaces. In *Proceedings IEEE Visualization '03* (2003), IEEE Computer Society, pp. 131–138.

[LMG97] LÖFFELMANN H., MROZ L., GRÖLLER E.: Hierarchical Streamarrows for the Visualization of Dynamical Systems. In *Visualization in Scientific Computing '97* (1997), Eurographics, Springer-Verlag, pp. 155–164.

[LMGP97] LÖFFELMANN H., MROZ L., GRÖLLER E., PURGATHOFER W.: Stream Arrows: Enhancing the Use of Streamsurfaces for the Visualization of Dynamical Systems. *The Visual Computer 13* (1997), 359–369.

[LSH04] LARAMEE R. S., SCHNEIDER J., HAUSER H.: Texture-Based Flow Visualization on Isosurfaces from Computational Fluid Dynamics. In *Data Visualization, The Joint Eurographics-IEEE TVCG Symposium on Visualization (VisSym '04)* (2004), Eurographics Association, pp. 85–90,342.

[LvWJH04] LARAMEE R. S., VAN WIJK J. J., JOBARD B., HAUSER H.: ISA and IBFVS: Image Space Based Visualization of Flow on Surfaces. *IEEE Transactions on Visualization and Computer Graphics 10*, 6 (Nov. 2004), 637–648.

[PR99] PEIKERT R., ROTH M.: The Parallel Vectors Operator - A Vector Field Visualization Primitive. In *Procceedings of IEEE Visualization '99* (1999), IEEE Computer Society, pp. 263–270.

[SBH*01] SCHEUERMANN G., BOBACH T., HAGEN H., MAHROUS K., HAMANN B., JOY K. I., KOLLMANN W.: A Tetrahedral-based Stream Surface Algorithm. In *Proceedings IEEE Visualization 2001* (Oct. 2001), pp. 151–157.

[Tou97] TOUTIN T.: Qualitative Aspects of Chromo-Stereoscopy for Depth-Perception. *Photogrammetric Engineering and Remote Sensing 63*, 2 (Feb. 1997), 193–203.

[vW93] VAN WIJK J.: Implicit Stream Surfaces. In *Proceedings of the Visualization '93 Conference* (Oct. 1993), IEEE Computer Society, pp. 245–252.

[vW03] VAN WIJK J. J.: Image Based Flow Visualization for Curved Surfaces. In *Proceedings IEEE Visualization '03* (2003), IEEE Computer Society, pp. 123–130.

[War98] WARE C.: Color Sequences for Univariate Maps: Theory. Experiments, and Principles. *IEEE Computer Graphics and Applications* (Sept. 1998), 41–49.

[War00] WARE C.: *Information Visualization: Perception for Design*. Morgan Kaufmann, 2000.

[WE04] WEISKOPF D., ERTL T.: A Hybrid Physical/Device-Space Approach for Spatio-Temporally Coherent Interactive Texture Advection on Curved Surfaces. In *Proceedings of Graphics Interface* (2004), pp. 263–270.

[WEHE02] WEISKOPF D., ERLEBACHER G., HOPF M., ERTL T.: Hardware-Accelerated Lagrangian-Eulerian Texture Advection for 2D Flow Visualizations. In *Proceedings of the Vision Modeling and Visualization Conference 2002 (VMV-01)* (Nov. 21–23 2002), pp. 439–446.

[WHE01] WEISKOPF D., HOPF M., ERTL T.: Hardware-Accelerated Visualization of Time-Varying 2D and 3D Vector Fields by Texture Advection via Programmable Per-Pixel Operations. In *Proceedings of the Vision Modeling and Visualization Conference 2001 (VMV 01)* (Nov. 21–23 2001), pp. 439–446.

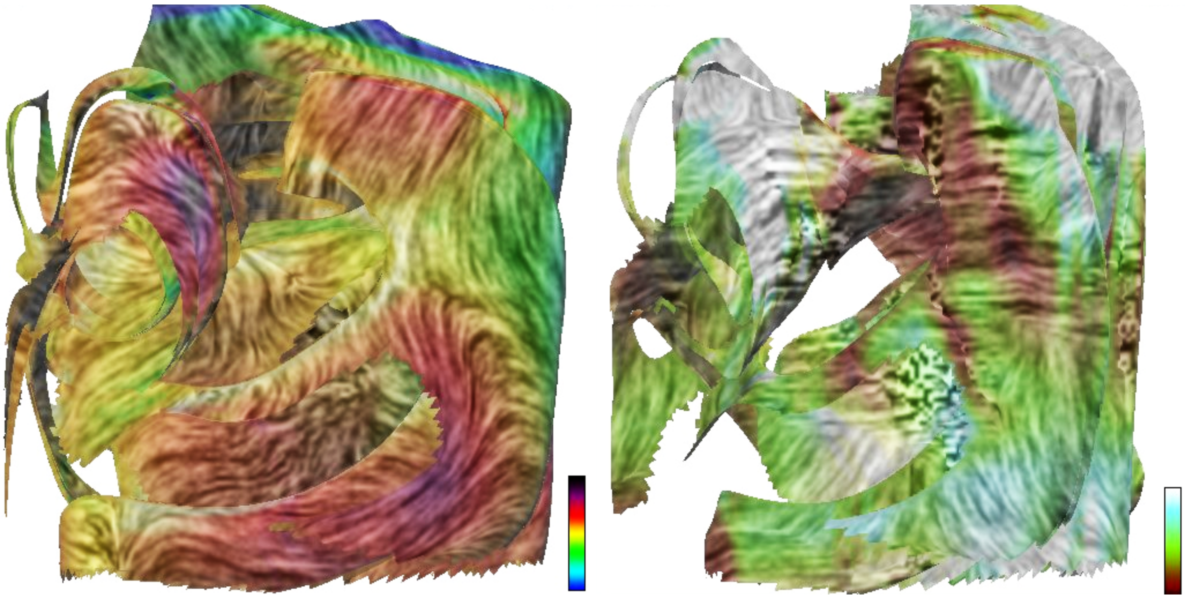

Figure 9: *(color plate) (left) A hybrid stream surface–texture advection visualization the tumble pattern of motion from the simulation results of a gas engine. In this case, texture properties are advected according to vorticity and color is mapped to helicity. (right) A hybrid stream surface-texture advection visualization with pressure gradient magnitude mapped to hue and texture advection applied to the pressure gradient field. The same stream surface is shown from a different view point.*