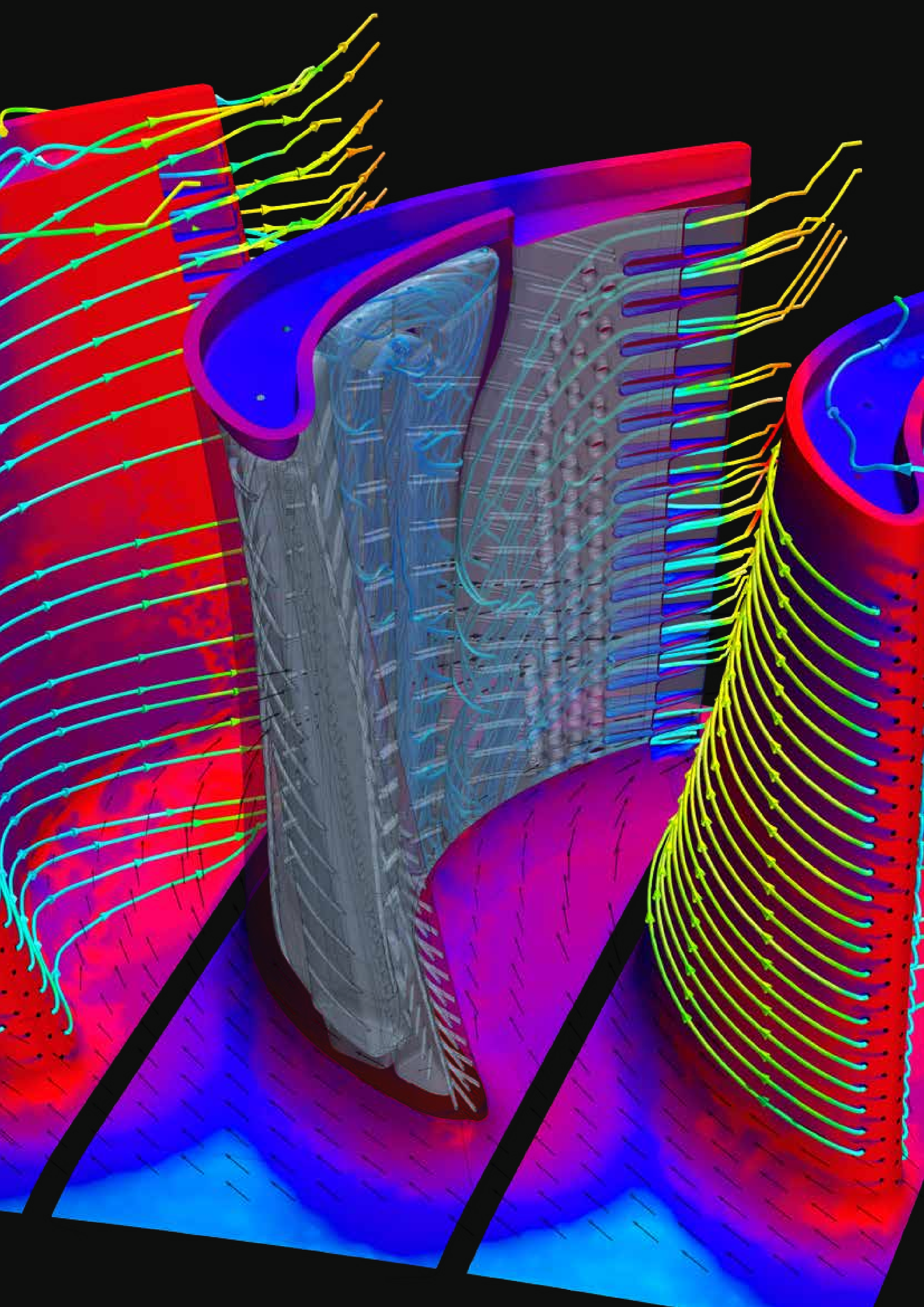

Improving cooling effectiveness of gas turbines through design exploration

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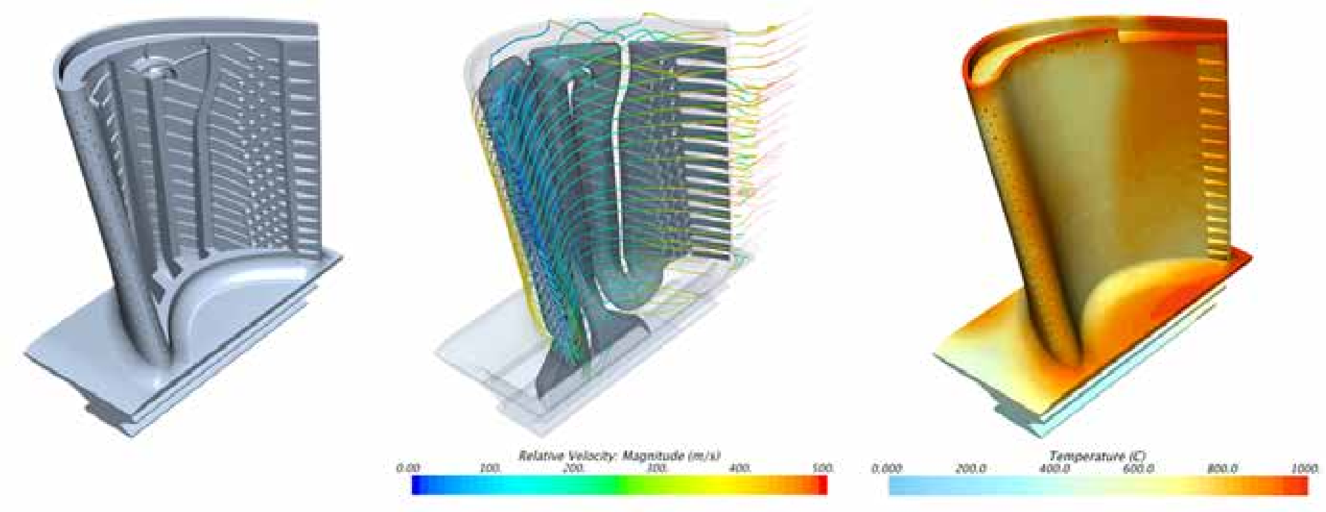
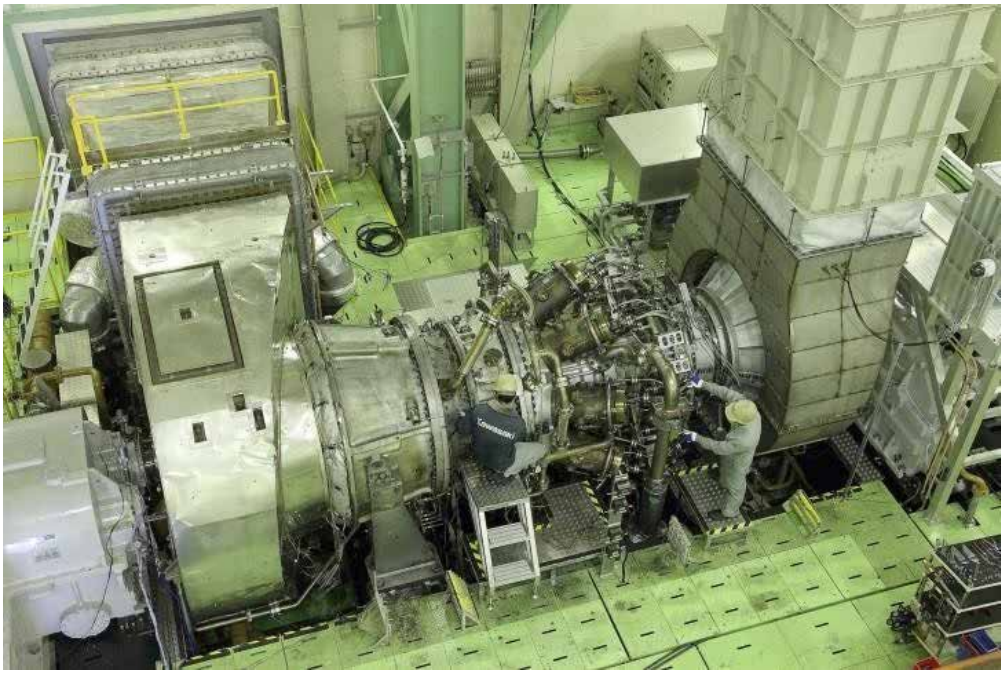


Figure 1: CFD simulation of gas turbine blade cooling showing
a) blade cutaway view
b) cooling air pathway and streamlines
c) blade surface temperature

Finding ways to increase temperatures at the combustor exit and high-pressure turbine stage inlet is key to boosting the efficiency of gas turbines. But higher operating temperatures jeopardize the integrity of the high-pressure turbine components, especially the vanes and blades, since modern turbine stage inlet temperatures exceed the melting points of turbine blade materials. To combat this, turbine blade designs have incorporated a technique known as film cooling.

During film cooling, cool air is bled from the compressor stage, ducted to the internal chambers of the blades and vanes, and discharged through small holes in the blade and vane walls. This air provides a thin, cool insulating layer along the surface of the blades and vanes.

The L30A from Kawasaki Heavy Industries (KHI) is the world’s most efficient gas turbine in its 30-megawatt power class. The L30A was developed by KHI with support from B&B-AGEMA GmbH, an engineering services firm based in Aachen, Germany, specializing in the design of energy conversion machinery and plants, most notably gas turbine components. Conjugate heat transfer (CHT), a computational fluid dynamics (CFD) technique for predicting thermal flux between a solid body and a gas or liquid flowing over or inside it, is a particular expertise of the firm, which has worked closely with Siemens PLM Software



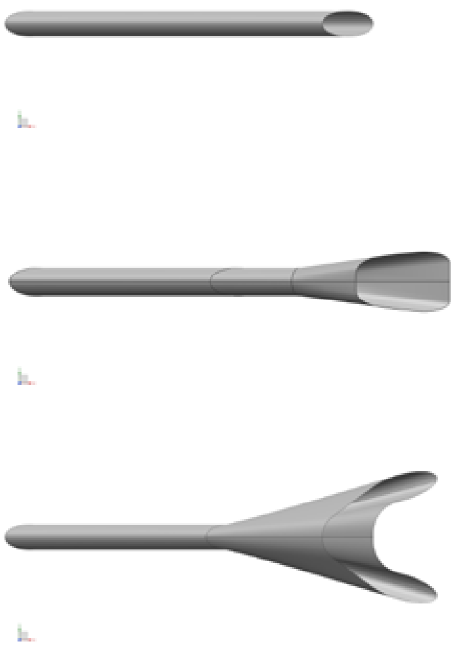


Figure 2: L30A on the heavy-duty gas turbine test rig at Kawasaki Akashi Plant, Japan (top)
Figure 3: Film cooling hole geometries: cylindrical (top), fan-shaped (middle), Nekomimi (below)

to simulate 3D fluid flow and pioneer new CHT methods.

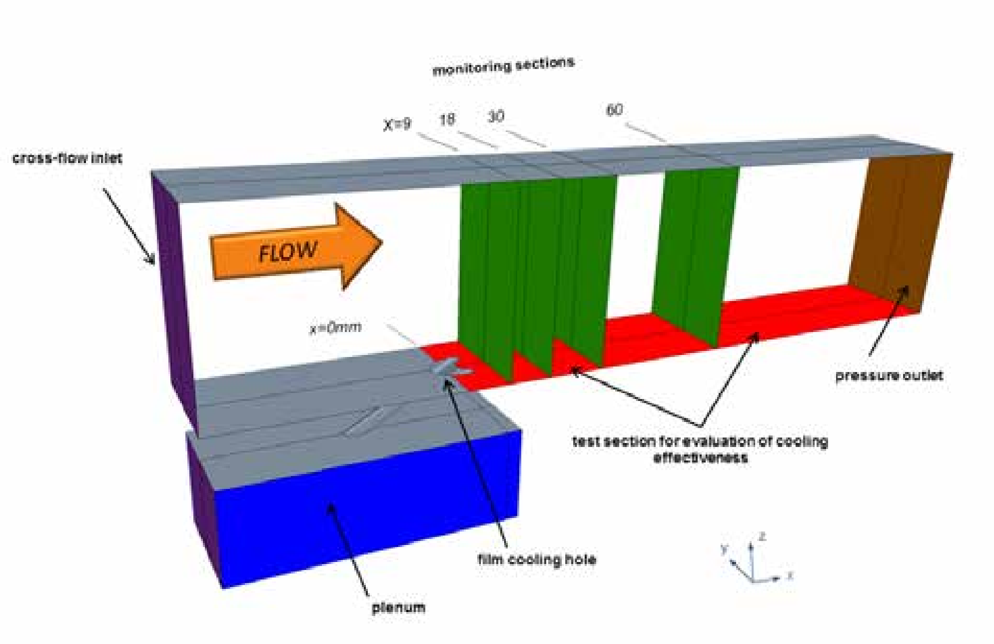
Cooperation between B&B-AGEMA and KHI began in the 1990s when KHI sought B&B-AGEMA's help to apply CHT methods to improve internal cooling of its turbine blade designs. B&B-AGEMA developed novel film cooling technology that, instead of conventional cylindrical holes, used fan-shaped holes to direct the flow of the air jets, thereby increasing their cooling effectiveness.

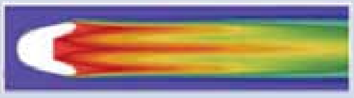
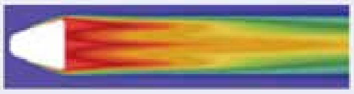
Specifically, from the 2000s on, B&B-AGEMA used CFD methods for film cooling simulations (1999-2002) and developed a technique known as double jet film cooling (1999) as well as the "Nekomimi" film cooling technology described below (2008). This work hinged on KHI's recognition that further technological advances would require an increasing reliance on fluid thermal modeling, simulation, and design exploration.

For some years, B&B-AGEMA and KHI applied STAR-CCM+® Software to perform design space exploration manually – that is, slowly and iteratively – to study the cooling effectiveness of different shaped holes in gas turbine blades, including shapes that the two companies nicknamed nekomimi which is Japanese for cat's ears, reflecting the visual appearance of the holes.

The computational domain used to virtually test the cooling effectiveness of different shaped holes (figure 4) consists of a main cross-flow duct and a plenum for the coolant supply, connected by the film cooling hole. The walls at the lateral sides are defined as symmetry planes in order to represent a row of film cooling holes – typical for gas turbine applications.

The plenum serves as cooling air supply for the film cooling hole. The adiabatic film cooling effectiveness has been spatially averaged on the surface highlighted in red.



Hole shape	Adiabatic film cooling effectiveness 0 – 1	Cooling effectiveness (averaged value on scale from 0-1)	Mass flow rate [g/s]
Nekomimi		0.330	10.17
Fan		0.343	14.85

The domain width and length is equal for all configurations; this allows comparison between different cooling hole designs with similar coolant mass flow rates, as they have the same cooling air consumption per unit area.

As illustrated in figure 5, for one particular comparison, a similarly-sized Nekomimi hole results in approximately equal film cooling effectiveness at a significantly lower mass flow rate compared to the fan-shaped hole. Note that on the normalized scale from 0-1 that is typically used for cooling effectiveness, red=1 (better) while violet=0 (worse).

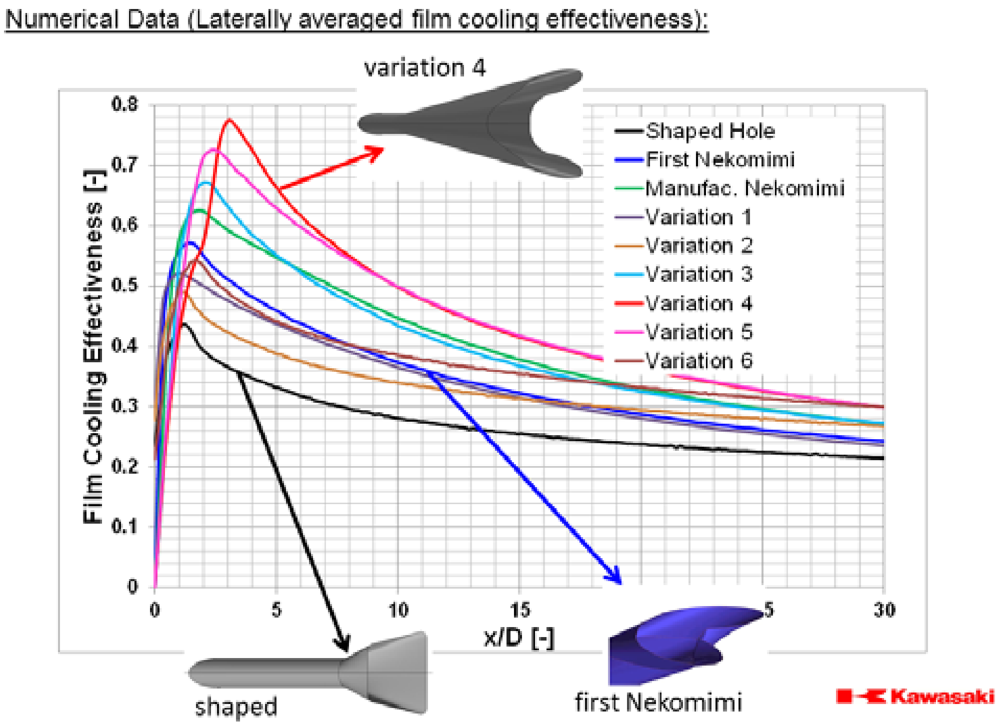
The result has been profound cooling improvements of 200 percent to 300 percent in the nekomimi designs over reference shaped holes – technology that has been co-patented by KHI and B&B-AGEMA.

How film cooling works and the Nekomimi hole advantage

The air used in the film cooling of gas turbines is extracted from the turbine's high-pressure compressor, so increasing the amount of air used for cooling decreases the thermal efficiency of the turbine. Furthermore, film cooling leads to mixing losses and reduced total temperature within the hot gas passage of the turbine. These inefficiencies can be ameliorated by finding ways to reduce the amount of cooling air needed, and to establish a more homogenous solid temperature distribution.

The cooling fluid injection through a hole leads to a "jet in cross-flow" situation, shown in figure 7. Secondary flow structures, including rotating vortices, are generated by interaction between the coolant jet and the cross-flow which can degrade film cooling effectiveness. These degradations

Figure 4: Computational domain used to virtually test the cooling effectiveness of different shaped holes (top)
Figure 5: Comparison of cooling effectiveness and mass flow rate for a Nekomimi versus fan-shaped hole (below)



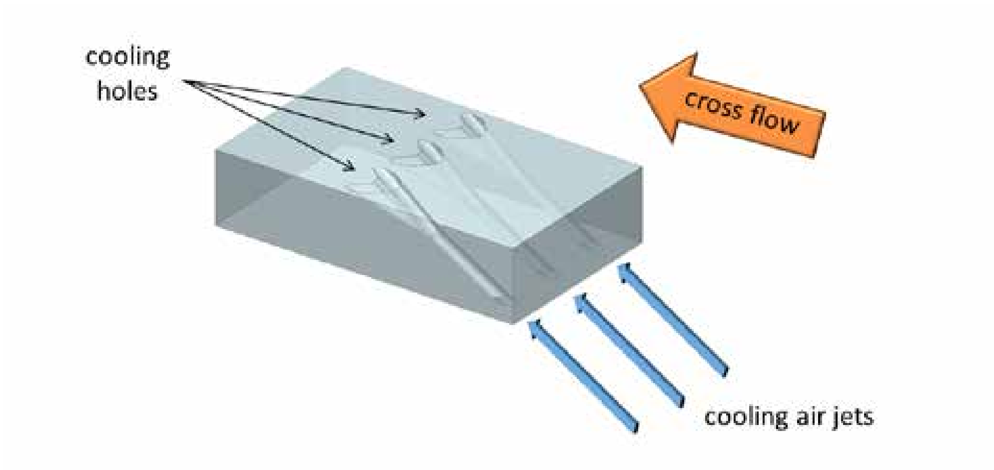


Figure 6: Film cooling effectiveness improved more than 200 percent from shaped hole to best Nekomimi (top)
Figure 7: Each cooling hole is a jet in cross-flow (below)

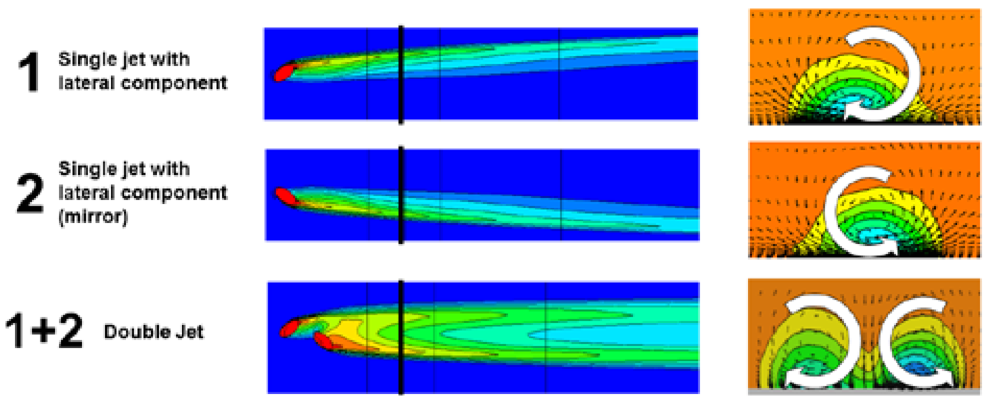
can be remedied by using a shaped-hole exit instead of a round hole, which leads to reduced momentum flux ratio between the coolant and cross flow at the cooling-hole exit (caused by the flow deceleration inside the diffusor part of the shaped hole), and a Coandă effect which facilitates the flow hugging the wall behind the hole. To reduce the undesirable mixing between the coolant and the hot gas, thus preserving a cooling layer near the surface of the turbine blade, double jet film cooling (DJFC) technology was introduced by B&B-AGEMA engineers in 1999.

The Nekomimi technology

In 2008, B&B-AGEMA debuted a novel hole design derived from the DJFC concept; the Nekomimi technology. This combines the two cylindrical holes of the DJFC within a single hole design to overcome the inefficiency of the air supply situation. This was achieved by shifting the holes of the DJFC configuration to the same streamwise position (figure 9, step 1), uniting both holes (figure 9, step 2) and replacing the two supply holes with a central one (figure 9, step 3).

Automated design exploration of the Nekomimi shape

Recently B&B-AGEMA and KHI decided to automate their design search through the use of HEEDS™, the design exploration software from Siemens PLM's Red Cedar Technology subsidiary, and the HEEDS-based Optimate+™ add-on module for STAR-CCM+. This change makes it possible



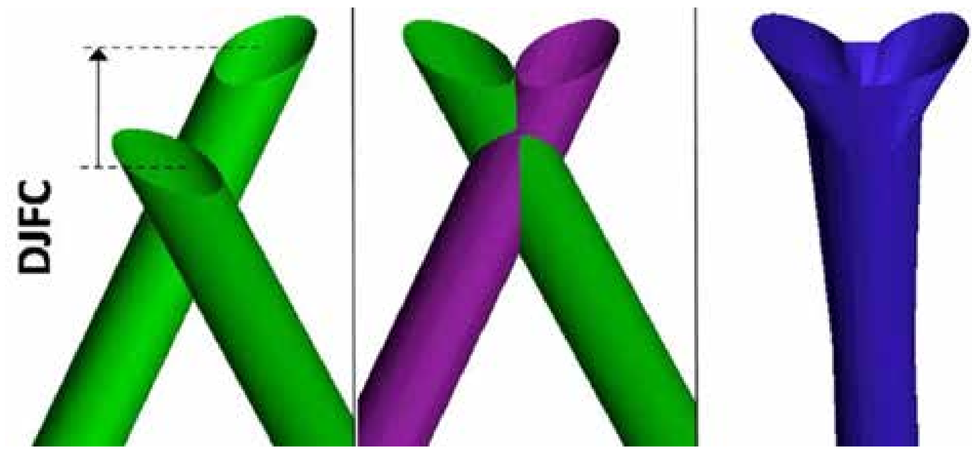


Figure 8: Double jet film cooling
Figure 9: Nekomimi design concept: a) step 1 (DJFC); b) step 2; c) step 3 (Nekomimi)

for them to evaluate hundreds of designs in the time previously required to assess just a handful, methodically comparing large numbers of traditional fan-shaped hole designs to Nekomimi-shaped holes.

Engineers from KHI and B&B-AGEMA worked with Siemens PLM to carry out an intelligent and automated search of the design landscape to identify nekomimi designs meeting conflicting objectives: low coolant mass flow rate and high adiabatic film cooling effectiveness on the test section. The parameters defining the shape of the Nekomimi holes (figure 10) were varied over 349 fluid dynamic simulations to generate a Pareto frontier of designs representing the best tradeoffs between the two objectives. Additionally, the design landscape of a laidback fan-shaped film cooling hole was searched over 299 simulations as reference in order to show the advantages of the Nekomimi technology.

Design search procedure

Optimate+ was used for the automated design exploration process, STAR-CCM+ for fluid flow and heat transfer simulation as well as geometry modeling of the fan-shaped holes, Siemens NX for parametric geometry modeling of the Nekomimi-shaped holes, and HEEDS post for visualizing and interpreting results, outlined in figure 11.

Optimate+ selects a set of design parameters and requests the CAD modeler to generate updated geometry. Then Optimate+ directs STAR-CCM+ to import the new geometry, automatically create an appropriate discretized mesh of the solution domain, and simulate the fluid flow and heat transfer. Optimate+ interactively reports the simulation results and predicted performance characteristics back to the engineer through a visualization tool named HEEDS Post.

Optimate+ intelligently uses the performance metrics to select a new set of design variables for the hole shape and repeats the process in an effort to discover better performing designs in a limited number of design evaluations. The engineer is also free to collaboratively influence the

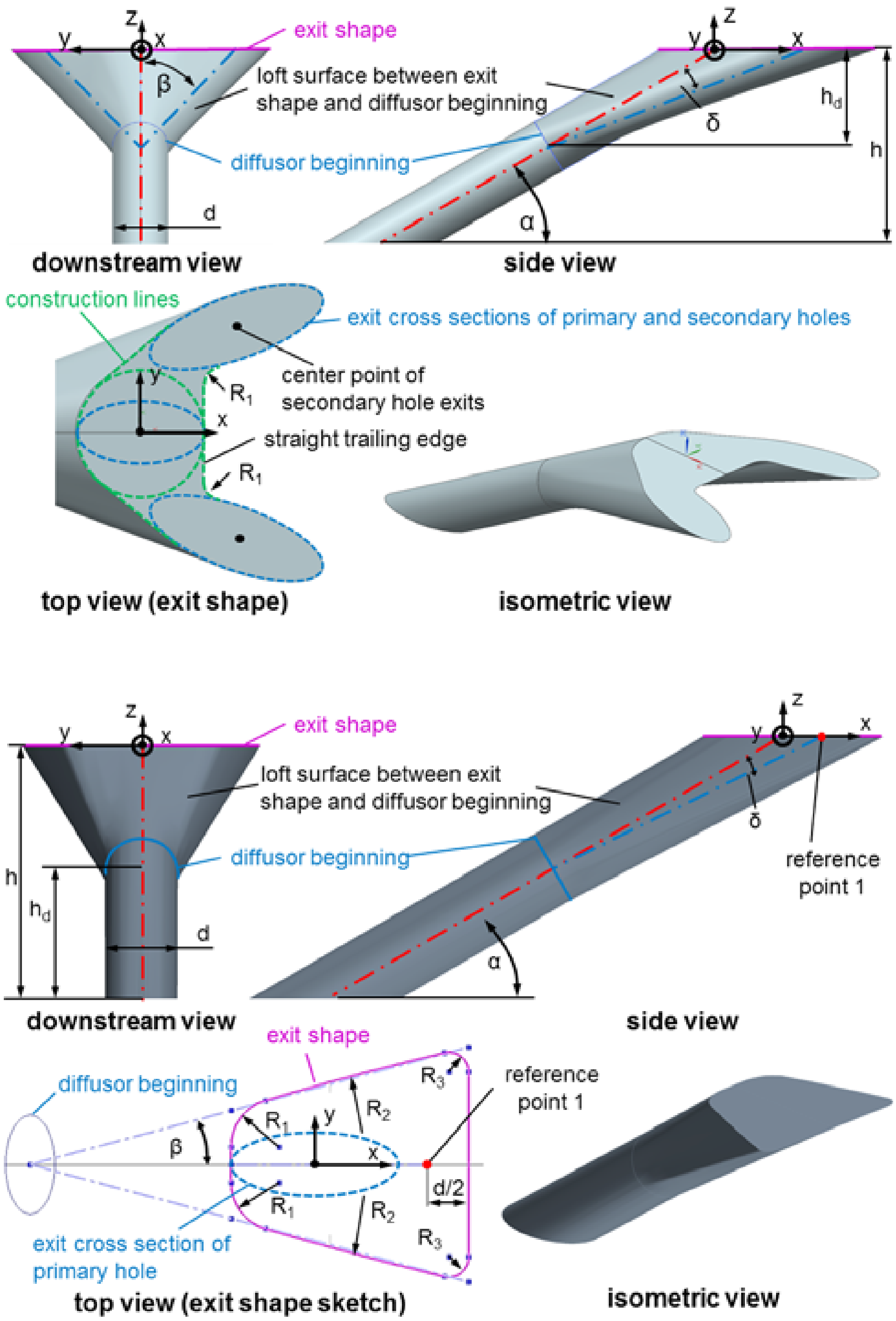


Figure 10: Nekomimi design parameters (top); reference fan-shaped-hole parameters (below)

"This work hinged on KHI's recognition that further technological advances would require an increasing reliance on fluid thermal modeling, simulation and design exploration.The result has been profound cooling improvements of 200 percent to 300 percent in the Nekomimi designs over reference shaped holes – technology that has now been co-patented by KHI and B&B-AGEMA.This novel approach makes it possible to build a database of the best Nekomimi cooling-hole designs for a variety of pressure ratios and coolant mass flow rates."

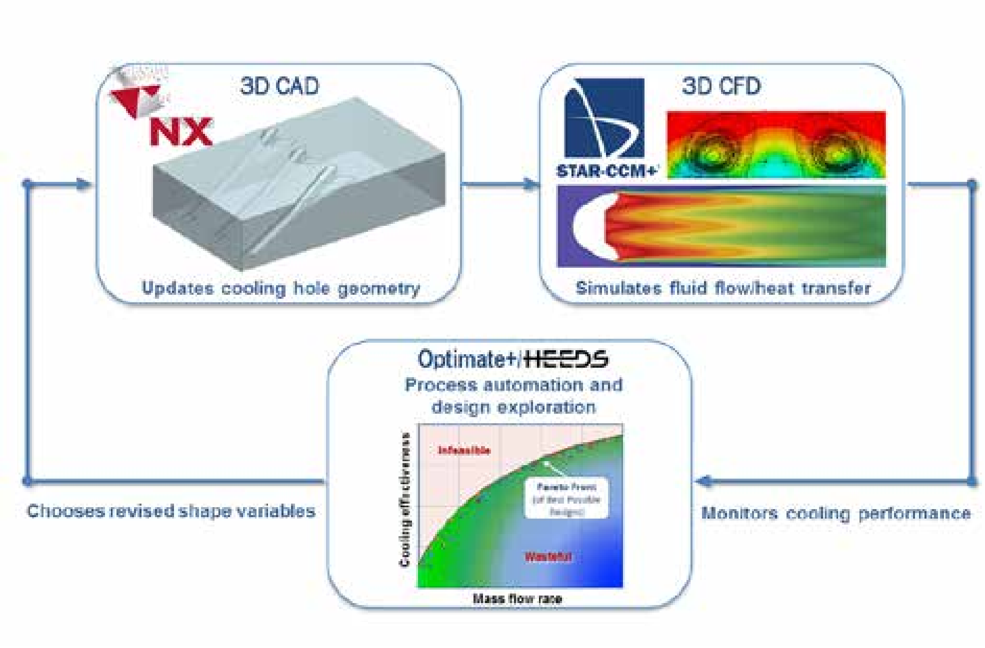
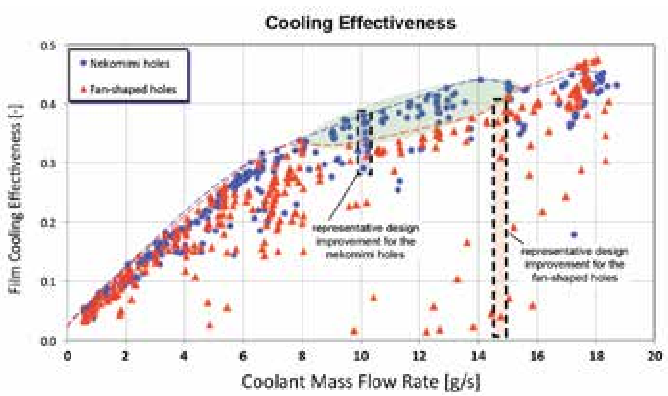


Figure 11: Automated design exploration procedure



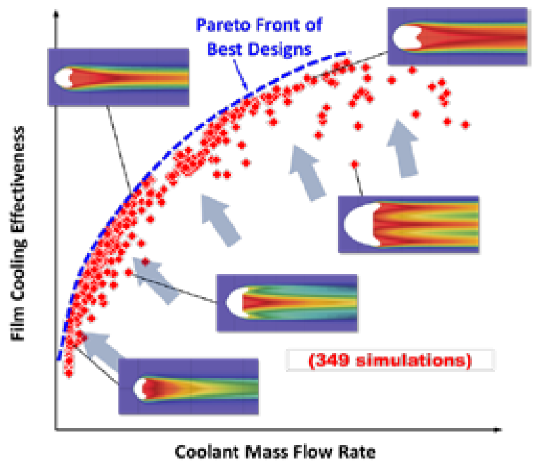


Figure 12: Film cooling effectiveness for all tested Nekomimi and fan-shaped film cooling hole designs (left)
Figure 13: Pareto front of best Nekomimi designs as trade-off between higher film cooling effectiveness versus lower coolant mass flow (right)

search by injecting designs to be evaluated based on intuition.

Design exploration results

The review of the results of the best possible hole shape is demonstrated by the Pareto front in figure 12 and shows the best-possible Nekomimi holes (blue dash-dotted line) and fan-shaped holes (red dash-dotted line) within the design space. These fronts show that the Nekomimi technology has significantly better spatially-averaged film cooling effectiveness for coolant mass flow rates between 8 g/s and 17 g/s. Below and above that range, both cooling hole concepts can reach comparable values for cooling effectiveness.

Also, analysis of two representative sets of simulation results (black dashed-line boxes) shows that for fan-shaped cooling holes, when the design parameters are not carefully chosen, counter-rotating vortices dominate the secondary flow structures and worsen the cooling effectiveness. In contrast, the Nekomimi shape delivers more consistently effective cooling performance across a wide range of design parameters.

This novel approach makes it possible to build a database of the best nekomimi cooling-hole designs for a variety of pressure ratios and coolant mass flow rates. From this database, cooling-design engineers can select the best design to achieve higher cooling effectiveness and lower cooling air consumption (figures 12 and 13).

For all kinds of film cooling holes, this study strongly enhances basic understanding of secondary flow phenomena and their impact on cooling effectiveness. Further, it proves the value of automated design space exploration for solving a broad range of standard engineering problems.