Energy and utilities

B&B-AGEMA

B&B-AGEMA uses Siemens Digital Industries Software solutions for design space exploration

Product

Simcenter

Business challenges

Increase gas turbine efficiency

Elevate temperatures at combustor exit

Improve film cooling techniques

Keys to success

Use CHT to simulate air flow and blade metal temperatures

Perform design space analysis using HEEDS

Build a reference database of cooling hole designs

Results

Realized cooling improvements of 200 to 300 percent through the Nekomimi design

Evaluated hundreds of designs in the time previously required to assess a minimal amount

Achieved higher cooling effectiveness and lower cooling air consumption

Simcenter STAR-CCM+ helps energy consultancy firm improve gas turbine blade cooling

Simulating film cooling for best results

Finding ways to increase temperatures at the combustor exit and high-pressure turbine stage inlet is the key to boosting gas turbine efficiency. But higher operating temperatures jeopardize the integrity of the turbine's high-pressure 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 the 30-megawatt power class. The L30A was developed by KHI with support from B&B-AGEMA GmbH (B&B-AGEMA), an engineering services firm based in Aachen, Germany, that specializes in the design of energy conversion machinery and plants, most notably gas turbine components. B&B-AGEMA works closely with Siemens Digital Industries Software to simulate 3D flow and pioneer new conjugate heat transfer methods (CHT). B&B-AGEMA is recognized as an expert in CHT, a computational fluid dynamics (CFD) technique for

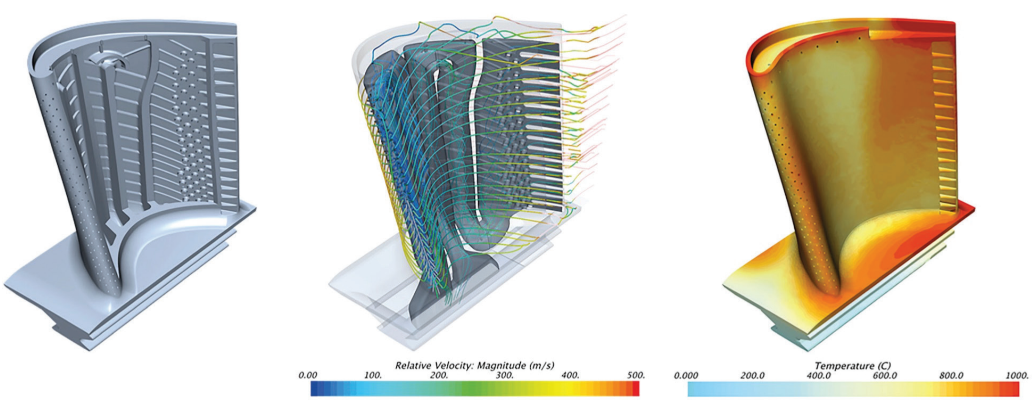

Figure 1: CFD simulation of a gas turbine blade showing: a) blade cutaway view; b) cooling air pathway and streamlines; c) blade surface temperature.

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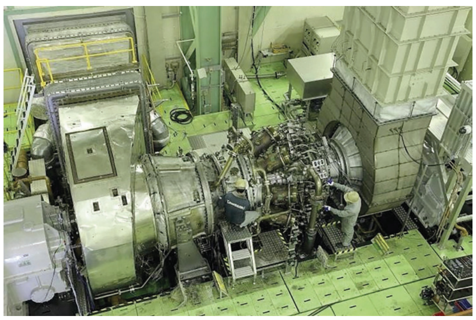

Figure 2: L30A on the heavy-duty gas turbine test rig at the Kawasaki Akashi Plant in Japan.

predicting thermal flux between a solid body and a gas or liquid flowing over or inside it.

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 the internal cooling of its turbine blade designs. B&B-AGEMA developed novel film cooling technology that, instead of using conventional cylindrical holes, used fan-shaped holes to direct the flow of the air jets to increase cooling effectiveness.

From the 2000s on, B&B-AGEMA used CFD methods for film cooling simulations. The company developed a technique known as double jet film cooling as well as the "Nekomimi" film cooling technology. This work hinged on KHI's recognition that technological advances would require an increased reliance on fluid thermal modeling, simulation, and design exploration.

Initially, B&B-AGEMA and KHI applied Siemens' Simcenter™ 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. This included shapes that the two companies nicknamed Nekomimi, which is Japanese for cat's ears, named for the visual appearance of the holes.

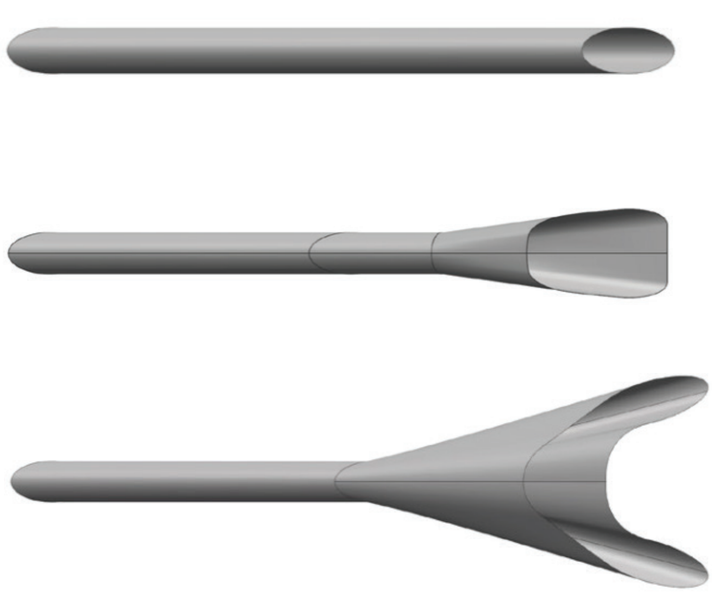

Figure 3: Film cooling hole geometries: cylindrical (top), fan shaped (middle), Nekomimi (bottom).

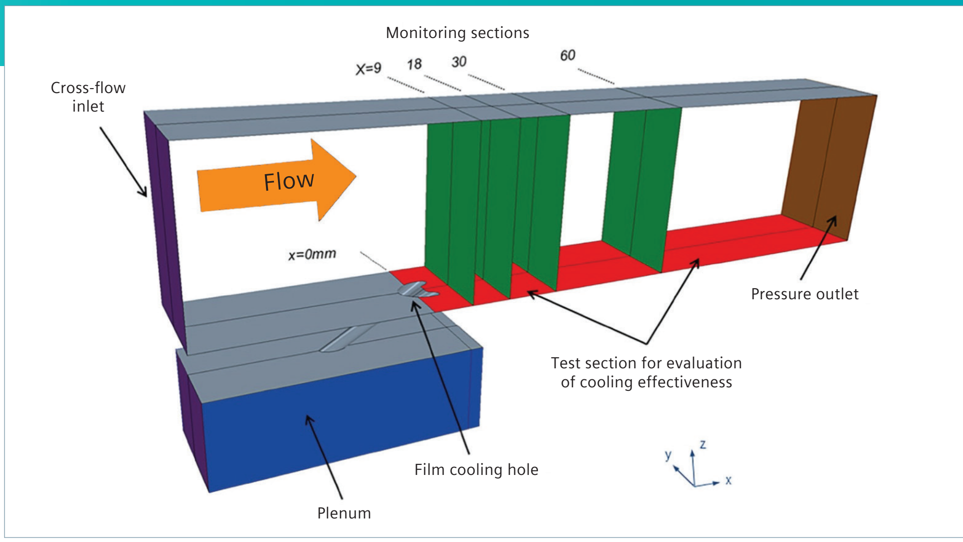

Figure 4: Computational domain used to virtually test the cooling effectiveness of different shaped holes. The adiabatic film cooling effectiveness has been spatially averaged on the surface highlighted in red.

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 in figure 4. The domain width and length are 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 resulted 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 to 1 that is typically used for cooling effectiveness red=1 (better) while violet=0 (worse).

The result, shown in figure 6, is significant cooling improvements of 200 percent to 300 percent in the Nekomimi designs over reference-shaped holes – technology that B&B-AGEMA and KHI has co-patented.

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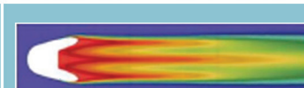
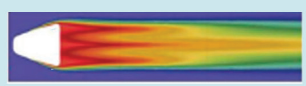
Hole shape	Adiabatic film cooling effectiveness (0 – 1)	Cooling effectiveness (averaged value on scale from 0-1)	Mass flow rate [g/s]
Nekomimi		0.330	10.17
Fan		0.343	14.85

Figure 5: Comparison of cooling effectiveness and mass flow rate for a Nekomimi versus fan-shaped hole.

Numerical data (laterally averaged film cooling effectiveness)

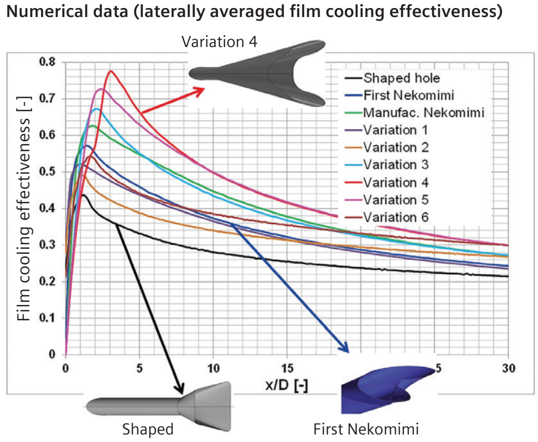


Figure 6: Film cooling effectiveness improves by more than 200 percent from shaped hole to first Nekomimi.

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 turbine's thermal efficiency. Furthermore, film cooling leads to mixing losses and reduced total temperature within the turbine's hot gas passage. These inefficiencies can be ameliorated by finding ways to reduce the amount of cooling air needed and establishing a more homogenous solid temperature distribution.

The cooling fluid injection through a hole leads to a "jet in cross-flow" situation (figure 7). Secondary flow structures, including rotating vortices, are generated by the interaction between the coolant jet and the cross-flow which can degrade film cooling effectiveness. These degradations can be remedied by using a shaped-hole exit instead of a round-hole exit, which leads to a 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, B&B-AGEMA introduced double jet film cooling (DJFC) technology 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 air supply inefficiency. 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).

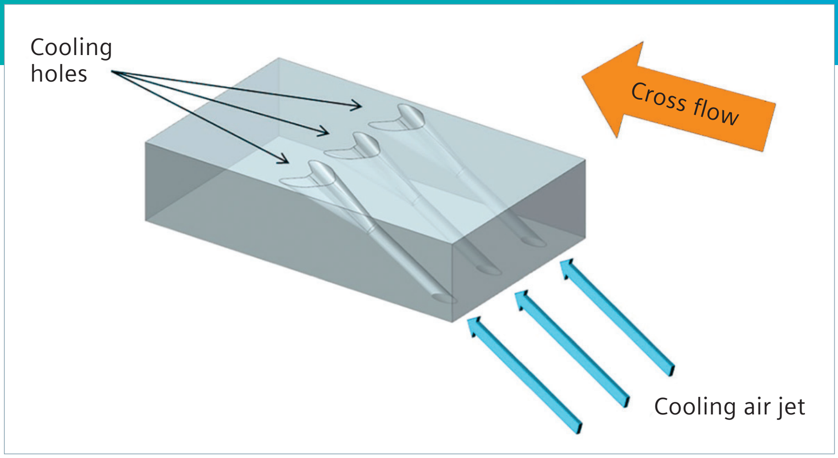


Figure 7: Each cooling hole is a jet in cross-flow.

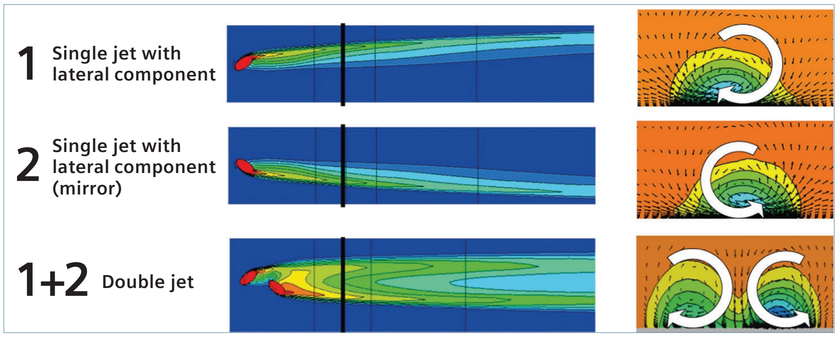


Figure 8: Double jet film cooling.

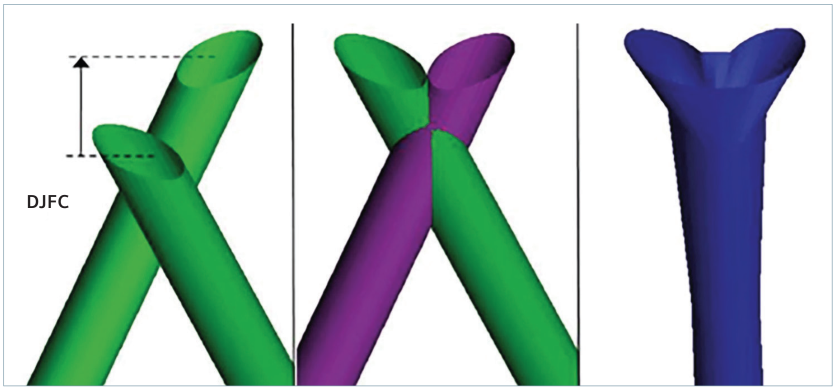


Figure 9: Nekomimi design concept: step 1 DJFC (left); step 2 (middle); step 3 Nekomimi (right).

Automated design exploration of the Nekomimi shape

B&B-AGEMA and KHI next decided to automate their design search by using Siemens' HEEDS™ software, a powerful design space exploration software package. This allowed B&B-AGEMA and KHI to evaluate hundreds of designs in the time previously required to assess just a handful, methodically

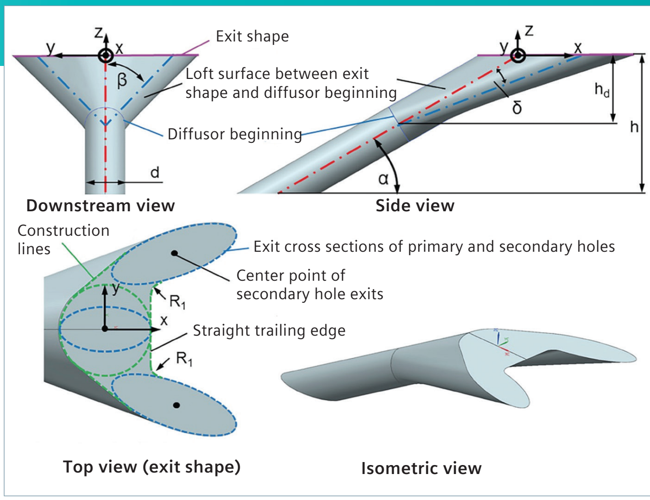


Figure 10a: Nekomimi design parameters.

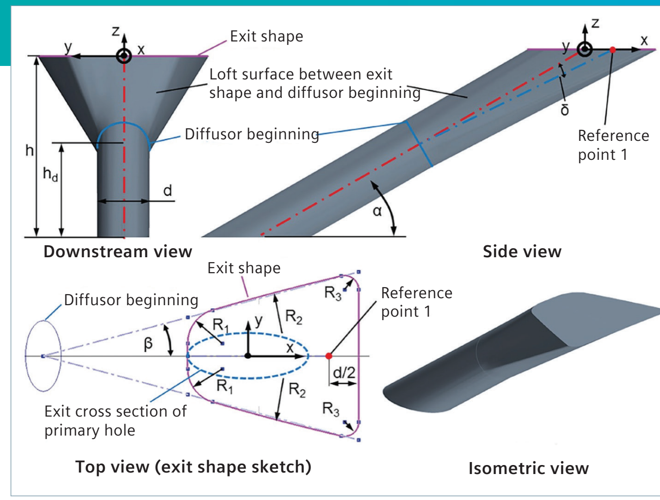


Figure 10b: Reference fan-shaped hole parameters.

comparing large numbers of traditional fan-shaped hole designs to Nekomimi-shaped holes.

Engineers from B&B-AGEMA and KHI worked with Siemens to conduct an automated search of the design landscape to identify Nekomimi designs while 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 10a) were varied over 349 fluid dynamic simulations and generated a Pareto frontier of designs, representing the best trade-offs between the two objectives. Additionally, the design landscape of a laidback fan-shaped film cooling hole was searched in over 299 simulations as a reference in order to show the advantages of the Nekomimi technology.

Design search procedure

The automated design exploration process was driven via HEEDS. Siemens' NX™ software was used for parametric computer-aided design (CAD) geometry modeling, with Simcenter STAR-CCM+ being used for fluid flow and heat transfer simulation.

For each simulation, HEEDS selected a set of design parameters and requested the CAD modeler (NX) to generate updated geometry. Simcenter STAR-CCM+ then imported the new geometry, automatically creating an appropriate discretized mesh of the solution domain and simulated the fluid flow and heat transfer. The results were interactively reported back to the user via HEEDS.

HEEDS intelligently used performance metrics to select a new set of design variables for the hole shape and repeated the process to discover better performing designs in a limited number of design evaluations.

From this database, cooling-design engineers can select the best design to achieve higher cooling effectiveness and lower cooling air consumption.

This study proved the value of automated design space exploration for solving a broad range of standard engineering problems.

Solutions/Services

Simcenter STAR-CCM+
siemens.com/simcenter

HEEDS
siemens.com/heeds

Customer's primary business

B&B-AGEMA is a German engineering company that provides consulting and research and development services to the turbomachinery and power plant industry.
www.bub-agema.de

Customer location

Aachen
Germany

The engineer collaboratively influenced the 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 11 and showed the best-possible Nekomimi holes (blue dash dotted line) and fan-shaped holes (red dash dotted line) within the design space. These fronts showed that the Nekomimi technology had significantly better spatially-averaged film cooling effectiveness for coolant mass flow rates between 8 grams/second (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) showed that for fan-shaped cooling holes, when the design parameters are not carefully chosen, counter-rotating vortices dominated the secondary flow structures and worsened the cooling effectiveness. In contrast, the Nekomimi shape delivered more consistently effective cooling performance across a wide range of design parameters.

This novel approach made 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 11 and 12).

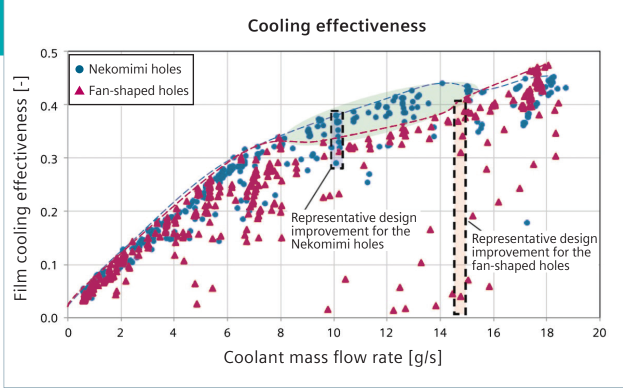


Figure 11: Film cooling effectiveness for all tested Nekomimi and fan-shaped film cooling hole designs.

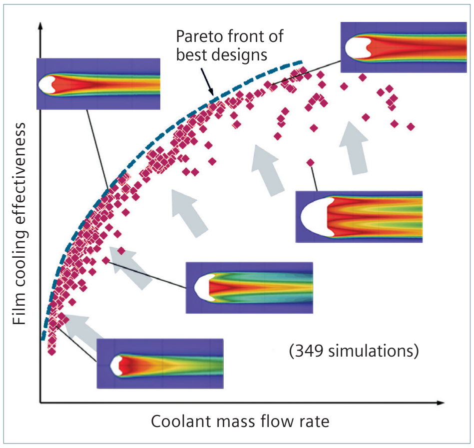


Figure 12: Pareto front of best Nekomimi designs as trade-off between higher film cooling effectiveness versus lower coolant mass flow.

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

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