"With FloEFD, the configuration of the simulation is made from within the CAD software, which eliminates the need for exporting/importing geometry. The software also has features such as automatic meshing, a case configuration wizard and integrated post processing, all from within the CAD software."

Arne Lindgren, Halmstad University, Sweden

Image Credit: Koenigsegg Automotive AB

Sports Car Brake Cooling Simulation with CAD-embedded CFD

By Arne Lindgren, Halmstad University, Sweden

Brake cooling is a crucial area in motorsport and sports car engineering. A recent thesis project by Arne Lindgren of Halmstad University in Sweden considered different cooling solutions for the extreme conditions of super cars. The project, conducted for super car manufacturer Koenigsegg Automotive AB, had the objective to design an efficient brake cooling solution for their latest model, the Regera. (Figure 1)

Regera, which means "to reign" in Swedish, is the first Koenigsegg car with hybrid-technology, the combined power of its internal combustion engine and its electric motors exceeds 1,500 horsepower. Such a powerful car needs effective and reliable brakes. During a braking event from 300 to 0 km/h, the average brake power is over 1 MW in the Regera.

Koenigsegg Automotive AB is a Swedish company founded in 1994 by Christian von Koenigsegg. The first prototype was completed in 1996 and the series production of their CC8S model started in 2002 [2]. The Koenigsegg CCR became the fastest production car in 2005 and the CCX model took the Top Gear lap record in 2006 with a time that wasn't beaten for over two years. In 2014 the One:1 model was introduced, the world's first production car with a hp-to-kg curb weight ratio of 1:1. The company employs approximately 120 staff including an engineering department which consists of about 25 engineers.

Lindgren evaluated several brake cooling designs for the Regera in his thesis. For his CFD simulations he used FloEFD™ embedded in CATIA V5 from Mentor Graphics – experimental testing being deemed too expensive and lacking in acquisition of certain flow data [1].

While dedicated brake cooling is not necessary for ordinary passenger vehicles, it is a huge challenge for sports cars that must tolerate racing conditions. The cooling effect of the ambient air is normally sufficient for ordinary car brakes during normal driving conditions. Modern road vehicles are equipped with internally vented brake discs (at least at the front axle, and usually also at the rear). The internal vanes help to pump air through the disc, internal channels are where the biggest heat dissipation takes place [1].

Over-heating of brakes can lead to a number of problems:

- Friction material degradation;
- Thermal stress in the brake disc, which can lead to distortion and stress cracks; and
- Brake fluid vaporization in the brake caliper.

These failures can lead to partial or complete loss of braking, which is very serious.

With regard to racing cars and cars for track driving, this issue becomes more complex. Special cooling ducts which direct ambient airflow to the brakes are used to ensure sufficient cooling performance taking into account the more frequent braking intervals that occur during track driving.

Brakes are mainly cooled through the heat transfer method called convection, where a fluid absorbs heat and transports it away from the hot object. Lindgren focused his work on improving the convective air cooling of the brakes, and limited his studies to the front axle brakes as this is where heat generation is at its greatest. The brake cooling solution that was used on the previous generation of Koenigsegg cars was used as a baseline for the cooling simulations.

The baseline design consists of inlet ducts in the front bumper of the car (that captures ambient airflow) and flexible hoses that channel the air to ducts (or nozzles), which are mounted on the wheel bearing carriers and direct the cooling air towards the center of the brake discs. (Figure 3) For the simulations, CAD models of the relevant geometry were provided by Koenigsegg which were used for the embedded CFD simulations.

Figure 1. Koenigsegg Regera

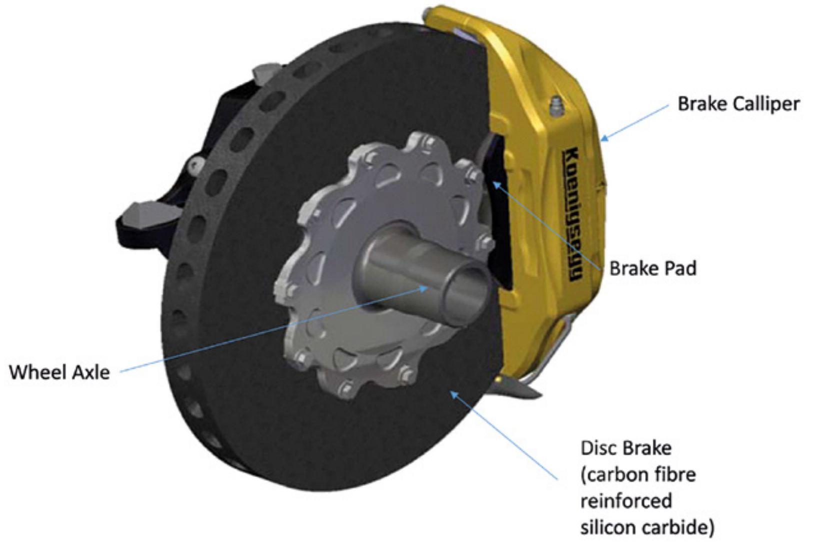


Figure 2. Koenigsegg Regera front brake.

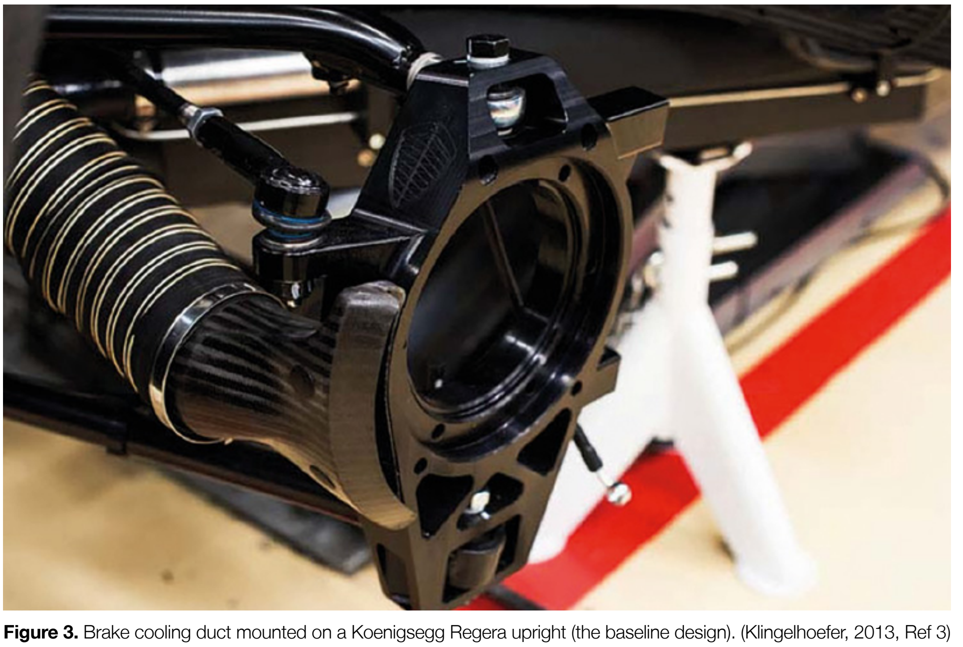


Figure 3. Brake cooling duct mounted on a Koenigsegg Regera upright (the baseline design). (Klingelhoefer, 2013, Ref 3)

The main geometries used in the simulations were:

- The brake discs made of Carbon fibre-reinforced silicon carbide (C/SiC), diameter 396 mm and thickness 38 mm, equipped with radial ventilation channels;
- The brake pads;
- The brake caliper;
- The upright (or wheel bearing carrier);
- The hollow wheel axle;
- The 19" wheel rim with tire; and
- The wheelhouse geometry.

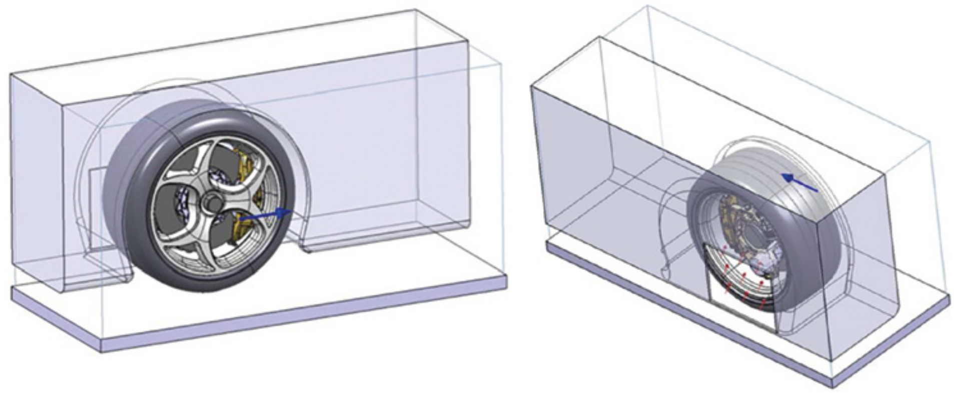


Figure 4. The geometrical wheelarch model (blue arrow indicates ambient airflow direction)

After simulating the baseline configuration, different brake duct concepts were generated and their cooling effect was simulated. The same computational model was used for both baseline and concept simulations, only the brake duct geometry and, naturally, the position of the duct inlet boundary conditions were changed. The simulations were conducted directly within the 3D geometry models in the CATIA V5 embedded FloEFD™ CFD software. This allowed for efficient simulation of complex geometries. An efficient and productive workflow was found as a result of the automatic meshing function, the case configuration wizard, the post processing features, and because geometry could be modified directly within the CAD environment [1].

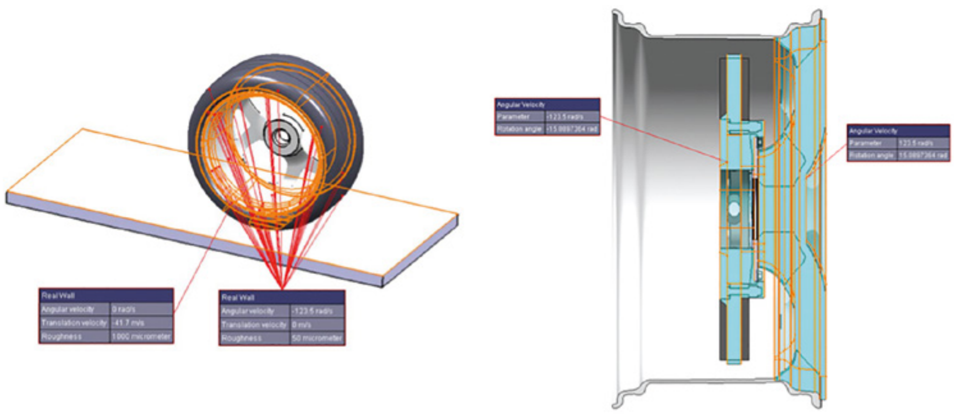


Figure 5. Wheel and ground boundary conditions. Rotating regions highlighted in turquoise

As to the objective of the project was to investigate many concepts, a reasonable calculation time was required. Therefore, a complete simulation of the entire vehicle was not expedient. A partial car body with wheelhouse was used as well as wheel and the brake as assemblies (figure 4) with similar dimensions and ground clearance as the Regera.

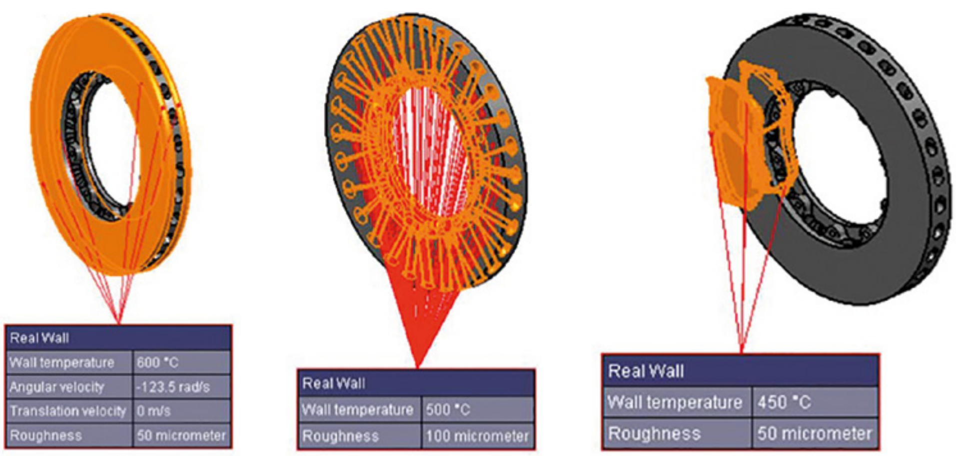


Figure 6. Disc and pad with FloEFD wall boundary conditions

The ambient velocity was defined as 150 km/h, which is a typical average speed on a race track. An additional airflow from the radiator was applied on the inboard side of the wheelhouse (figure 4, red arrows). The

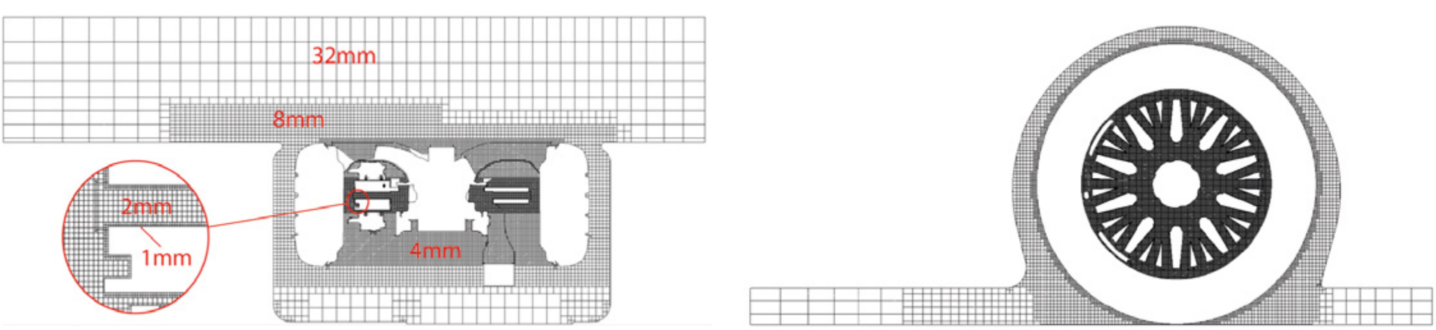


Figure 7. FloEFD Computational mesh of the Wheel, Brake Disc and Wheel Housing

airflow through the flexible hose from the inlet ducts in the front bumper was modeled as a pressure to get a realistic flow rate for all possible brake duct designs. The rotation of rotationally symmetric geometries, such as the tires and brake disc friction surfaces, were defined with wall conditions. The FloEFD sliding mesh approach was applied to the non-rotationally symmetric parts. A 3D body (rotating region) is used to define which geometries should rotate, in this case the rim spokes and brake disc channels. A translation velocity of 150 km/h was applied to the ground (figure 5) to include ground effects. Only convection was considered for the CFD simulations as this is the easiest heat transfer process to influence and has a proportion of about 60 – 90 % of the total heat dissipation. The surface temperatures applied on the surfaces of the parts (figure 6) were based on values recorded by Koenigsegg during track testing. The simulation was conducted with approximately 3.5 million cells (figure 7) using the FloEFD two-scale wall function technique, which enables the use of a coarser mesh than would be otherwise necessary in traditional CFD codes.

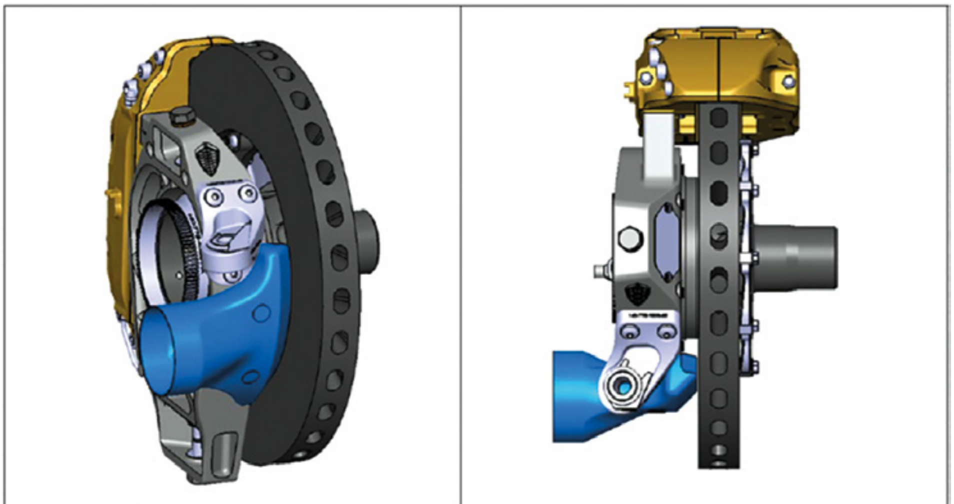
The concepts were based on Lindgren's own ideas, observed brake cooling designs, and observations in other applications while taking into account only concepts that are possible to manufacture. 12 different concepts were investigated using the described FloEFD boundary conditions. With the given settings, the simulation time was approximately 24 hours on a computer with a six-core Intel Xeon E5 CPU at 3.5 GHz and 32 GB RAM.

The baseline simulation results are shown in figure 8.

Each concept was compared with the baseline concept. The investigations focused on the cooling of the brake discs as most of the braking energy goes into the discs. The approach was to increase the convective cooling by breaking up the temperature boundary layer, which can be done by using high air velocity or by introducing turbulence. In addition, other design criteria were considered to ensure that the solution withstands forces, vibrations, and temperatures etc., that occur in driving conditions.

The investigations showed that a local improvement of the airflow often led to worse heat dissipation in other areas simultaneously. The airflow rate was simply not sufficient to improve the cooling over larger surfaces.

Another early discovery was that the design of the cooling channels in the brake discs could be improved. But the brake disc design was outside the scope of this project so it was not studied further. The break-through was the idea of putting the brake duct inlet in the center of a wheel axle that has radial channels. This resulted in higher hose flow rate because the radial channels in the axle and the brake disc work together as a centrifugal fan. Finally, this concept was supplemented by a "passive" cooling design (not relying on airflow from the hose), realized by two ring-shaped plates perforated with slots. (Figure 10) The simulations showed that these plates improved the cooling of the discs friction faces, but Lindgren expresses



Description:	The design used on previous Koenigsegg models. Nozzle that blows towards the axle centre.								
Result:	**Heat transfer rate [W]**							**Mass flow rate [kg/s]**	
	Total	**Disc centre**	**Disc channels**	**Disc inside**	**Disc outside**	**Pad inside**	**Pad outside**	**Hose**	**Channels**
	14481	2837	5448	3003	2170	482	508	0,183	0,104

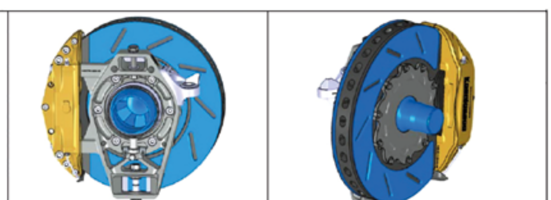
Figure 8. Baseline brake duct highlighted in blue and table with the numerical results from FloEFD

Concept 8									

Description/ Idea:	Inlet duct in the centre of a modified axle with radial channels, the through hole is plugged. The brake disc centre is closed off so no air is escaping there.								
Difference from baseline	**Heat transfer rate**							**Mass flow rate**	
	Total	**Disc centre**	**Disc channels**	**Disc inside**	**Disc outside**	**Pad inside**	**Pad outside**	**Hose**	**Channels**
	14%	34%	19%	-2,0%	1,9%	4,8%	6,1%	41%	48%
Comment /Analysis:	Good overall improvement, better cooling on most surfaces. Axle channels and disc channels are working like a centrifugal pump and increases the hose flow rate which benefits the cooling.								

Figure 9. Overall view and FloEFD results for concept No. 8

Concept 12									



Description/ Idea:	Inlet through axle, chamfer added to radial channels inlets. Closed disc centre as in concept 8. Ring-shaped plates 8 mm from the disc inside and outside surfaces with flanged slots, similar to concept 11, but with inverted angle and deeper flanged slots (3,5mm from disc)								
Difference from baseline	**Heat transfer rate**							**Mass flow rate**	
	Total	**Disc centre**	**Disc channels**	**Disc inside**	**Disc outside**	**Pad inside**	**Pad outside**	**Hose**	**Channels**
	25%	-2,0%	28%	15%	78%	6,4%	10%	57%	71%
Comment /Analysis:	Good overall improvement, very big improvement on disc outside compared to concept 11.								

Figure 10. Overall view and FloEFD results for concept No.12

skepticism to these results as the simulations didn't include radiation (in reality the plates would reflect heat back to the disc). Concepts 8 and 12 were the most promising, although concept 12 needs further analysis or testing to see the effect of radiation. The designs of the concepts and the results given as the difference in percent from the baseline values are shown in figures 9 and 10. Concept 8 has the advantage that only a few relatively simple additional parts are needed.

From the almost infinite number of possible cooling solutions, 12 concepts were analyzed (figures 11 - 13) and compared with the baseline design from Koenigsegg. The two most promising solutions lead to an overall thermal improvement of 14% and 25%. Concept 8 was proposed as an enhancement, which had the hose inlet in the center of the wheel axle thus directing the cooling air through radial channels to the brake disc. FloEFD simulations indicated that the proposed design should result in 14% higher heat transfer rate compared to the previously used cooling solution. In addition to these cooling ducts, some passive cooling devices could also be considered in future.

In this study FloEFD was able to provide trend predictions within engineering timescales for a wide range of concepts although it was recommended that finer meshes and radiation effects be examined more in the future which require more computational resources. However, the CFD results described here indicate that when compared to brake cooling with the previous Koenigsegg ducts analyzed as a baseline, new concepts could be created, analyzed and developed in an easy iterative process. The simulations with the CATIA V5 embedded version of FloEFD made these investigations possible because creating a real prototype of each concept would lead to high cost and time requirements. The most promising solutions can now be investigated deeper in terms of structural analysis, manufacturing processes, and finally produced as a prototype.

References

[1] “Development of Brake Cooling”, Arne Lindgren, Bachelor Thesis in Mechanical Engineering, 15 credits, Halmstad 2016-05-20:

http://www.diva-portal.se/smash/get/diva2:938489/FULLTEXT01.pdf

[2] Koenigsegg website: http://koenigsegg.com/

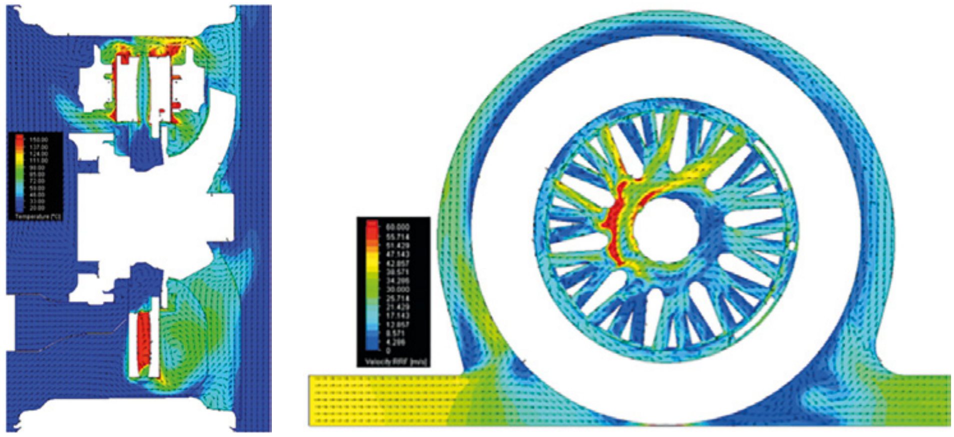


Figure 11. Baseline Case (a) temperature cut-plot on a horizontal plane through the wheel, and, (b) vector velocity on a vertical plane through the disc channels.

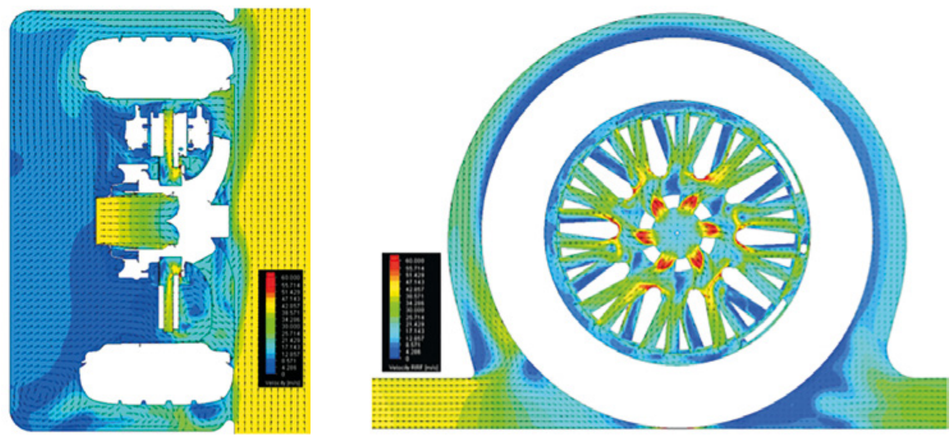
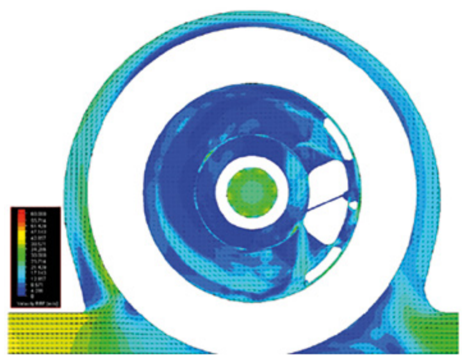
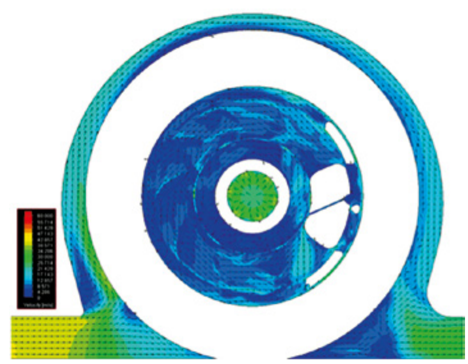


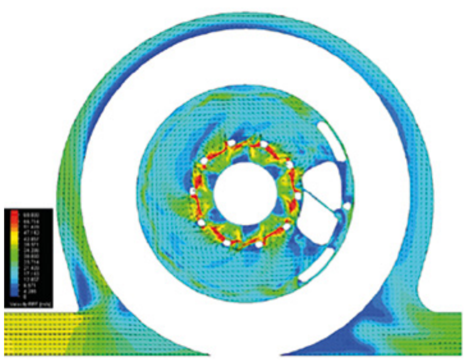
Figure 12. Concept 8 velocity cut-plot horizontal plane (a) through the wheel, and, cut-plot vertical plane through disc channels (b).



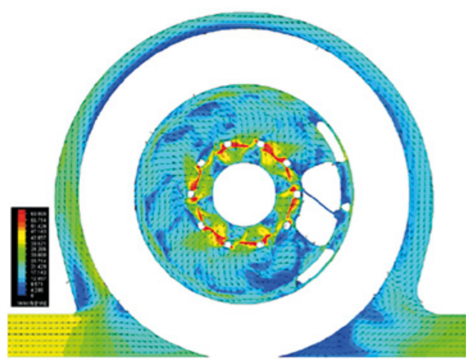
Concept 8, velocity 1 mm inside disc



Concept 12, velocity 1 mm inside disc



Concept 8, velocity 1 mm outside disc



Concept 12, velocity 1 mm outside disc

Figure 13. Comparison of Concept 8 and 12