ECOQUEST Report Summary

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Final Report Summary - ECOQUEST (Efficient Cooling Systems for Quieter Surface Transport)

Executive summary:

An indispensable subsystem in surface transportation vehicles (rails bound, automotive) is the engine cooling module with its demand of external energy and its sound emission. Under specific operational conditions the cooling system is the major noise source and the component with the second largest consumption of energy (after the engine). The overall objectives of ECOQUEST were novel contributions towards reduced noise radiation and decreased CO2 emissions by (i) revision of the general system layout, (ii) optimization of components from the thermal, acoustic and fluid dynamics viewpoint, and (iii) modification of the control strategy. For that, innovative complex multiphysics computational methods had to be developed - either by combination or by extension of known methods - and validated.

Project context and objectives:

Background

An important subsystem in surface transportation vehicles (rails bound, automotive and heavy duty) is the cooling unit. Present European standards for interoperability of rail bound traffic require low noise levels while manufactures need to meet the vehicle performance and energy efficiency requested by the operators. The stringent EU6 emission limits expected to come into effect will increase dramatically the demand for cooling power in road vehicles without accepting a noise penalty. Manufactures need innovative methods for reducing costs of development and testing and thus further improving their competitiveness in the global market.

The objectives are innovative contributions towards novel cooling units with reduced noise radiation and decreased CO2 emissions. We aim at new compact layouts, innovative heat management strategies and low energy/noise components. Intermediate objectives concern (i) implementation of an integrated simulation platform for noise mechanisms, scattering and propagation; (ii) development of design procedures for thermally and acoustically optimal cooling units; (iii) research on innovative fan designs and new passive noise control measures and their integration into novel cooling units. Mass produced automotive units and large locomotive systems produced at small numbers are considered simultaneously - strong synergies and cross-fertilization are expected.

WP2: Extension, validation, and integration of acoustic prediction methods

WP2 is concerned with the combination of different modeling strategies involved in the prediction of the noise emitted by generic cooling units. Regarding source modeling, we address individually the tonal and broadband noise and the broadband noise scattering. Combining the methods yields a simulation platform addressing all noise features. This integration/interfacing is performed with the aim of obtaining a seamless, yet non-proprietary simulation strategy.

WP3: Integrated design and mock-up tests

In WP3 realistic train and automotive environments are considered. The design of mobile cooling systems is revisited in a more integrated manner as compared to the state-of-the-art. Within a multidisciplinary study we optimize the thermal layout of cooling systems and the overall flow employing advanced numerical simulation tools. For the automotive application, a typical car platform is selected. For the specified heat dissipations, various module configurations are modeled and analyzed with system tools such as the multiphysics simulation software Kuli® and Flowmaster®. The cooling module has three baseline heat exchangers: a radiator for the cooling loop, a condenser for the climate control loop and a charge air cooler (CAC) for the turbocharged air loop. The consequent module configurations can then range from multi-layers layouts to side-by-side layouts and mixed versions. The initial single fan system configuration which restrains the design space to heater core that have an aspect ratio close to 1 (square configuration) is also relaxed to account for dual fan systems and heater cores that have aspect ratios closer to 2. Attempts are also made to have various fan system axial depths to allow for various design options such as axial, mixedflow or radial fans and fans with stators of different kinds. On the locomotive side, addressing all aspects of engine cooling requires a detailed view on the coolant efficiency ratio, noise emission and energy consumption, space required and weight, integratebility into a powertrain and packaging. Therefore in a first step a one-dimensional system analysis with respect to the thermal management of the cooling systems is performed. In a following step a parametric study by varying the cooling unit lay out is done. This includes number/size of radiators, number/size of fans, radiator at intake ore pressure side, variation of rotational speed, etc. Furthermore various options of controlling strategies for the cooling unit (e.g. slow acceleration of ventilator speed, predictive cooling, use of vehicle speed for cooling (bypass, flaps etc.)) are investigated. Eventually this simulation is combined with a holistic simulation of the vehicle on a track.

WP4: Full-scale tests

WP4 uses the outcomes from WP2 and WP3. The impact of the new design strategies is validated by full scale tests. Two full scale modules, one for car/truck and another one for locomotive are implemented in vehicles and experimentally investigated under realistic test conditions. The technologies developed are assessed with respect to thermal efficiency, energy consumption (CO_2-emission), noise benefits, packaging and costs. The results are used in the technology implementation plan. In addition, a high-performance numerical acoustics simulation method is adapted, validated by a separate series of small scale model tests at the acoustic laboratory and eventually used to predict the far field noise by the vehicles under the existing test environment. This is rated as an important tool for future component development e.g. with respect to the envisaged certification of the vehicle. WP4 is performed primarily by industrial partners to enable immediate exploitation of the results.

WP5: Exploitation plan and dissemination

WP5 deals with the overall assessment of the outcomes of the whole project, guidelines, exploitation plan and dissemination of the knowledge generated during the project beyond the Consortium.

The outcomes of the project are assessed in terms of technological break through and costs vs. benefits. With the assistance of the industrial partners USI compiles guidelines on new validated methodologies as well as new design rules.

Two exploitation managers (VAL and VTA) overview the evolving market situation and communicates this to Consortium members; they inform the Consortium on how the product requirements are affected by the evolution of international or local noise standards; they co-ordinate issues related to Intellectual Property Rights; they issue an Exploitation Plan aimed at technology implementation.

Project results:

Major progress was achieved in the fields of

- acoustic modeling and prediction

- cooling circuit simulation of mobile cooling units on realistic tracks

- energy efficient and low-noise axial fans

- modeling and application of acoustic absorbers

- advanced testing methodology

Some highlights of the technical improvements are:

- automotive cooling system: CO_2 reduction of 0.5 g/km, 4.5 dB sound reduction

- locomotive cooling system: CO_2 reduction of 51 g/km, 7 dB sound reduction

Subsequently, a set of achievements is described individually.

Near-field effects in tonal interaction noise from fans

In this Task, we focused on the role played by near-field terms in the acoustic scattering. Existing formulations, such as presented by Goldstein, discard explicitly the near-field terms to derive an elegant formulation for tonal fan noise, involving Bessel functions that represent the phase modulation related to Doppler effects. However, Roger showed recently that the near-field terms can account for important phase-shifting effects, which can play a significant role, even in the amplitude of the acoustic far field, if for example the edge of a semi-infinite plane is present in the near field of the fan. The work performed in this task pursued this analysis for several cases of interest to the present project. Firstly, the importance of near-field terms was assessed in free-field, in order to quantify the distance from the fan beyond which the far-field approximation can be retrieved. Secondly, the implementation of the fan as a source in the context of Boundary Element and Finite Element Methods was validated by placing it within a cylindrical straight duct with anechoic boundary conditions at both ends. This permits validation of the approach by comparison with the analytical solution based on the duct modes. The near-field solution was applied to the case of a Valeo fan, for which the BLHs were obtained through CFD simulations.

Analytical modeling of tonal Interaction noise from fans including installation effects

Facing the large variety of fan system configurations, generic test cases that can be treated analytically are useful for a better understanding of both the aerodynamic sound generating mechanisms and the main installation effects. The work was devoted to simple prediction models addressing two main mechanisms, namely rotor-stator or stator-rotor wake-interaction noise, and the potential-interaction noise of a rotor operating in the close vicinity of a downstream or upstream strut or obstacle. Only the tonal noise at the harmonics of the blade passing frequency was considered, and the broadband noise is addressed in another task.

RANS/LES based methods for broadband turbulence noise

In this task, the acoustic prediction methods described based on Amiet's theory for leading and trailing edge noise have been implemented and tested. We also pointed out the relative importance of both noise phenomena in rotating machine applications and the necessity to account for both of them in order to have a correct noise prediction in the whole frequency range. In addition we focused on the development of interfacing techniques between those acoustic prediction methods and LES/RANS incompressible computations. Innovative methods to take into account spanwise flow variations along the airfoil span were developed. This was required for rotating machine applications. Based on the necessary inputs for the acoustic methods and their respective extraction position, we developed a methodology to provide the required input data. The computational cost and accuracy of the new proposed methods compared to classical methods based on Curle's analogy have been evaluated. We measured the self noise and turbulence generated by locomotive heat exchangers. This data is also required for reliable sound prediction.

Self noise and turbulence generation by heat exchangers

The investigation of the heat exchangers is important to add their self-noise into the sound prediction tools and to estimate the turbulence generation which is an input to the fan noise modeling. Two heat exchangers were investigated which proved to have similar turbulence inducing characteristics. It could be revealed that the thin cooling fins have almost no impact on turbulence. In contrast, the ten times thicker water bearing ducts create an enormous turbulent intensity in the vicinity of the heat exchanger. Further downstream, the turbulence decays rapidly and reaches its minimum after around 250 mm. The maximum was found directly behind the test object (water bearing ducts) or at some 35 mm (cooling fins). Peak values amount to 35 %. Close to the minimum of turbulence, there is only little influence of the heat exchanger type and the impact of ducts is not measurable at all. The turbulent intensity then amounts to some 4 % with an exponential decay between the extremes. The decay roughly follows the empirical formula by Roach. A moderate influence of inflow velocity was revealed. Close to the heat exchangers, turbulence decreases through higher flow velocities. This effect is reversed further downstream. The inflow velocity furthermore effects the distance where the influence of the different obstructions vanishes. The integral length scale of turbulence shows a strong dependence on distance to the test object. In the first 150 mm it follows the empirical law by Roach, further downstream higher values are obtained.

Broadband noise scattering - theoretical modeling and simulation

The prediction of the broadband noise scattered by the fan environment involves several aspects: the prediction of the noise emitted by the fan towards the listener as if it were placed in free field (incident field), and the calculation of the scattered field in a second step. When the fan source is described in deterministic terms, i.e. when the wave fronts emitted by the fan are known in both phase and amplitude, the calculation of the scattered field by numerical means (Boundary Element Method or Finite Element Method) is relatively straightforward. However, in the present case the fan source is known in statistical terms, and the free field Power Spectral Density that is predicted by standard methods is not a suitable input to the numerical approaches cited above. The approach that has been pursued here consists in expressing the source field within a formalism compatible with the numerical software developed by LMS, following the Acoustic Transfer Vectors approach in particular. Another important point is the proximity of the fan blades with the acoustic environment. As a result, the classical formulations of Amiet are not applicable since they assume that the listener (or scattering surface in the present case) is located in the acoustic and geometrical far-field of the fan blade. Besides, the fan blades have to be segmented in order to account for the spanwise variation of the flow properties, and the long-span assumption cannot be used anymore.

Model test of a generic isothermal cooling unit

The objective of this task was the application of the aeroacoustic simulation tools developed in before to a cooling unit, specifically designed to permit the detailed validation of the flow and acoustic fields. The model is largely made of Plexiglas to allow PIV measurements, and is designed to be representative of a scaled-down locomotive cooling unit. The model was fitted upside down in an anechoic room of the von Karman Institute, permitting to measure the noise emitted outside of the module through the heat exchangers and inlet grid. The noise that would be radiated through the roof in the real configuration is here propagating through a duct equipped with azimuthal microphone arrays, for the investigation of the spinning acoustic modes. The flow field has been simulated using the OpenFOAM software from which the necessary inputs for sound predictions models were extracted. The incident broadband acoustic field is scattered on the mock-up geometry using a specific numerical methodology based on a Boundary Element Method validated in previous tasks. The heat exchanger is there represented by a lumped model characterized through transfer admittance matrix.

System auto/truck - thermal optimization

A system-level thermal optimization of automotive/truck cooling modules has been conducted using two different approaches. The first method consists in studying different configurations via a Kuli model and was applied to a Renault Laguna. The Kuli model was calibrated to account for the car's geometry by post-processing wind tunnel tests results. The second method is more general, and consists in running a numerical Design Of Experiment using Computational Fluid Dynamics in order to construct a neural network that is capable of computing a velocity map on the heat exchanger instantaneously. The velocity map takes into account upstream mean flow distortions due to the dissymmetry of the front-end air intake or to the cross-beam as well as the effect of the downstream blockage that is due to the combustion engine. The neural network covers 22 geometric and physical parameters and requires 129 simulations to be run in order to be initialized.

Sytem loco - thermal optimization

In this task, we focussed on the general layout and design of locomotive cooling unit including the complete system. First, the cooling system with respect to the thermal management, the noise emission, the energy consumption and the system layout was performed in a 1D simulation suite. In following steps this system was optimized with respect to the objectives of the ECOQUEST project. This parameter study includes controlling, strategy and layout variations of the total cooling system.

Innovative axial fan blades

New fans for the automotive and locomotive cooling systems were developed. The main objectives were increased energy efficiency and reduced sound emission.

First attempts to design the automotive fan used the analytical 2D fan design tool 'dAX' developed by USI. The designs were then simulated by VAL. However, it was found that the extraordinary design point prohibits this procedure for several reasons such that a decision was made to do without analytical methods and to optimize the fan blades by CFD simulations embedded in an evolutionary optimization algorithm. Evolutionary algorithms are powerful optimization tools which are able to satisfy several target functions simultaneously. The incorporation of constraints can easily be implemented and the algorithm is less prone to converge to local optima than other optimization tools. The biggest disadvantage is the huge computational effort which was, however, accepted for this project.

In the present application, the target function was maximization of total-to-static efficiency and was evaluated by RANS simulations. Since the main dimensions as well as the rotational speed are fixed, the optimization parameters only comprise the blade design. The resulting optimal parameters are discussed in detail in Deliverable D3.3. In the final report, only the very surprising result of the stagger angle distribution is considered. The optimal stagger angle decreases from hub to mid-span and increases again towards the shroud. This is in contrast to common design assumptions in which the stagger angle always decreases from hub to shroud due to the difference in circumferential velocity. The finding of the unexpected optimal distribution is the main reason for the massive increase of efficiency from 50 to 70%.

Innovative passive noise control

Within this project two different main objects for fan passive noise control have been examined both experimentally and theoretically; the heat exchanger and inlet parallel baffle silencers. For the first object seven heat exchangers were experimentally assessed, using a modified version of ISO 15186-1:2000, to test the acoustic transmission for a diffuse field. In addition a sample from each heat exchanger type was cut out and tested by measuring the acoustic two-port in a duct, i.e., the transmission and reflection at normal incidence were determined. Theoretically, the basic configuration is assumed to be a matrix of parallel and rectangular narrow channels. The developed model is based on a so called equivalent fluid for an anisotropic medium. It is mainly dependent on the heat exchanger geometry combined with the Kirchhoff model for thermo-viscous wave propagation in narrow tubes. This model is a continuation of earlier work by Yan and Åbom. In order to reduce the transmission through heat-exchangers they can be fitted with parallel baffle silencers. In ECOQUEST a new type of such silencers using Micro Perforated Panels (MPP:s) have been designed and tested.

Prediction of noise emitted by full-size cooling systems

The prediction of the noise scattered by the fan environment involves several aspects: the prediction of the noise emitted by the fan towards the listener as if it were placed in free field (incident field), and the calculation of the scattered field in a second step. When the fan source is described in deterministic terms, i.e. when the wave fronts emitted by the fan are known in both phase and amplitude, the calculation of the scattered field by numerical means (Boundary Element Method or Finite Element Method) is relatively straightforward. The difficulty lies in the source representation. An additional difficulty is the presence of the scatterer in the near field which significantly makes the computation of the incident more complex. This step is extensively presented in deliverable D2.1 for tonal fan noise scattering. When the fan source is known in statistical terms (broadband fan noise), and the free field Power Spectral Density that is predicted by the methods explored in Task 2.2 is not a suitable input to the numerical approaches cited above. The approach that has been pursued in the project has consisted in expressing the source field within a formalism compatible with the numerical software developed by LMS, following the Acoustic Transfer Vectors approach in particular. Another important point is the proximity of the fan blades with the acoustic environment. As a result, the classical formulations of Amiet are not applicable since they assume that the listener (or scattering surface in the present case) is located in the acoustic and geometrical farfield of the fan blade. Besides, the fan blades have to be segmented in order to account for the spanwise variation of the flow properties, and the long-span assumption cannot be used anymore. Those steps are extensively presented in deliverable D2.2 for the incident broadband fan noise and in D2.3 for broadband fan scattering. In task 3.1 and 3.2, system level Auto and Loco cooling units have studied and CFD analyses have been performed by Valeo and University of Siegen respectively. The CFD analyses were used to perform acoustic analyses and convergence studies based on the approaches mentioned above. The acoustic analyses and studies are presented and compared to experimental results obtained in task 3.6 for the auto and 3.7 for the loco.

Automotive mock-up tests

In this work the interest is the sound power generated by automotive cooling units. The units were mounted in a wall between two rooms, one room being the ISO qualified reverberant test room at the Marcus Wallenberg Laboratory (MWL), KTH. By rotating the units this room could be used to determine both the up- and down-stream sound powers using the ISO 3747 method and a reference source. The back ground noise has been canceled out from the final results. All measured results in this report have been performed using Spectra PLUS - FFT Spectrum Analyzer and the results are presented as 1/3 octave-bands.

Locomotive mock-up tests

All experiments were conducted at the test field of VTA in Heidenheim-Mergelstetten. The cooling unit was operated without thermal load, i.e. no coolant was pumped through the heat exchangers. Moreover, only the rear part of the cooling module is considered, wherefore the front fan remained in standstill and the module was divided by a wooden separating plate. The fan was driven by a hydraulic motor in the fan hub which is also used in the full-scale tests and in everyday operation. Hydraulic pressure was provided by a pump driven by an electric motor. The drive was operated in emergency mode meaning that there is no throttling of in the hydraulic cycle and the rotational speed of the fan is directly controlled by the speed of the electric motor (= pump speed). Potential throttling of the air flow due to contamination of the heat exchangers was simulated by covering 10 % of the heat exchanger area with strips.

Full-scale tests of automotive cooling unit

Tests on vehicle tests were conducted in the climatic wind tunnel located at La Verriere (France). The selected car was equipped with Valeo components, designed and prototyped during the ECOQUEST project. Various configuration of the cooling module have been used and have lead to the recording of several sets of results. Two types of cooling were tested, i.e. the direct cooling with the baseline, and the indirect cooling with the 'Ultimate CoolingTM' module. On this latter, several adaptations of fan system were tested: a solution with a dual fan system, a solution with an optimized single fan system, and an innovative solution with a concept of semi-radial fan.

Full-scale test of loco cooling unit

The locomotive full-scale tests were conducted in June 2012 in Luneburg, Germany. It was distinguished between three states of the locomotive:

1. Locomotive in standstill with fixed fan speed and twelve microphones placed around it.

2. Six fixed microphone positions passed by the locomotive at constant speed (40 km/h)

3. Onboard measurements with three microphones attached to the locomotive which drove a 23 km test track with 500 t of load and realistic driving conditions with respect to velocity, acceleration, breaking, and terrain slopes

Acoustic environment effects

This task is about the experimental characterization of the sound field around a simplified locomotive at 1/16 scale in semi-anechoic room, and the comparison with BEM simulations. Sources mimicking the fans or the air-inlet grids are located either on the top or on the sides of the mockup. A reflecting ground and an optional vertical rigid wall at different distances are considered. Sound is measured for broadband excitation in a horizontal plane between the locomotive and the wall (the so-called platform area), at equivalent height of human head. Sample post-processed data are discussed and interpretations of major observed effects are provided. Characterizing fan noise in absence of any surrounding surfaces provides key information on the sound generating mechanisms and is relevant for strategies of noise reduction at source. However exposure of passengers in the environment of a railway station involves other aspects related to the scattering of fan noise by the locomotive itself, on the one hand, and to multiple reflections and diffraction by architectural elements of the station, on the other hand. Typically people on a platform can be quite close to the locomotive or close to a vertical building wall at some limited distance. The effect of that wall on the annoyance can be as important as the sound generation itself. This is why an academic experiment has been decided in the ECOQUEST program to address such a situation of practical interest. The main objective is to identify key effects that are expected for a locomotive in the presence of two perpendicular half-planes. Typically it is focused on the difference between sound fields with and without side-wall, for the sake of assessing the ability of some prediction models to reproduce it. However many configurations can be encountered in real stations and a complete modeling of the environmental effect would not be tractable if all geometrical details were included. It is guessed that major effects only involve design details that remain of the same order of magnitude as the acoustic wavelengths of interest. This led to the following criteria for the definition of the experiment.

- The true shape of the locomotive can be strongly simplified. It can be manufactured ignoring geometrical details. Geometrical simplification is also the condition for the problem to remain tractable numerically using a boundary-element method (computational effort provided by partner LMS). Furthermore diffraction is more pronounced at relatively low and middle-range frequencies, whereas high frequencies could be described using simplified approaches based on ray-tracing theory.

- The ground-only (full ground plane) configuration is considered as a reference case, corresponding to the absence of building around the machine. Two configurations with distances 2L and 3L of the vertical half-plane (wall) to the side of the locomotive are investigated, L being the width of the locomotive. The measurements make sense in horizontal planes that are believed representative of human hearing, typically 1.6m at full scale.

- The scale of the mockup must be compatible with the instrumentation and the size of the anechoic room. The value 1/16 has been selected. This is why the measuring plane has been fixed 10 cm above the ground.

Novel auto/truck cooling units: Guidelines on methodology, design and cost/benefits

Valeo has conducted during this project investigations on automotive engine cooling systems. The work included important considerations on energy efficiency, helping to reduce fuel consumption and CO_2 emission, and aiming also to reduced noise pollution. Even beyond the mere cooling module, the studies have considered the effects on the vehicle drag and on the climate control loop (air conditioning compressor and heat exchangers).

The work was conducted with the goal of building a platform for cooling module design that includes numerical methods and analytical models. All future studies on cooling systems will take advantage of these improved methodologies, and it is expected that new technologies and scientific progress could also be added progressively in this set of tools.

Many lessons have been made for thermal systems, ventilation systems, for integration into the vehicle. It must be added those acquired in the areas of modeling, simulation and optimization (thermal and acoustic). Several procedures have been developed and are used. Enhanced methodologies due the ECOQUEST project comprise: global performance prediction due to fan simulation, fan design by optimization methods, CAD of the shroud for fan system simulation with 'PCC' geometry, simplified module simulation, post-processing of global performances and flow distribution, unsteady simulation with various flow rates, tonal noise minimization with rotor stator interaction, unsteady simulation for tonal noise prediction, fan system selection according to customer specifications, KULI calculation with EXCEL control, dynamic modeling of an engine cooling system, aeraulic calibration of an engine cooling system - according to wind tunnel test results, air conditioning system modeling with KULI - AC system and cooling system interaction, and direct and indirect cooling system modeling with KULI.

A new best practice guidelines was created in the field of cooling module aerodynamic resistance and the effect on CO_2 balance considering drag and thermal management. This work presented earlier in the project has involved two different techniques that have been coupled. Another best practice guideline deals with fan performances on the cooling efficiency during MVEG cycle and the effects on the CO_2 balance of the vehicle.

Thermal performances have been predicted using a dual flow-stream technique that computes precisely heat exchanges between air flow and cooling fluid. Mechanical power needed for the cooling at different vehicle speed has been assessed and compared to thermal exchanges for different conditions. Final results are presented for NEDC driving cycle and different conditions, i.e. 24 or 33 °C and with or without climate control. Gains on CO_2 production are about 4 to 7% compared to base line, which represent about 0,1 to 0,2 g per km.

These gains are only due to the fan system and they represent a significant advance in terms of impact on the automotive fleet and regarding the additional cost which is null. It is even found that the single fan-system solution is almost at the dual fan system level, despite this latter is deemed more expensive, heavier and noisier. This is especially remarkable since the surface coverage of single fan system on the heat exchanger was lower than the dual one.. A better area ratio, which would appeal to less elongated exchangers (typically square section) could probably further improve the performance.

The project has promoted the development of techniques for analyzing the efficiency of vehicle thermal management. The numerical simulation has been widely used and it has provided predictions of aerodynamic and aerothermal performances. These tools have been implemented in some optimization processes based on a design of experiment, the construction of response surface using neural networks and research algorithms. All the methods investigated are incorporated in a virtual platform for development of cooling systems.

Significant progress has been made for complete simulation of the cooling system, either for cooling modules or for underhood conditions. Results were coupled with thermal modeling tools that provided assessment on CO_2 production during driving cycles. The analysis includes the complete system with engine cooling and climate control. These methods are applicable to systems with direct or indirect cooling as the one promoted by Valeo with Ultimate CoolingTM. This latter significantly improves the aerodynamics of the vehicle and the thermal management, which results in reduced production of CO_2.

Comparisons were made between different types of fan system, either with a single fan, or with 2 fans, or with innovative geometries such as the semi-radial fan. In terms of conception, it has been further demonstrated that the perfect adaptation of fan nominal operating point to the cooling module yields improvements and reduces the fan system power consumption.

Aeroacoustics has been considered during the development of analytical methods for predicting the tonal noise and its directivity, and through experiences dealing with effect of fan integration in the shroud on the acoustic power. In addition to the advances in the analysis and the modeling, micro-perforated plates for acoustic damping were tested and innovative stator geometries were produced.

These methodologies are gradually incorporated into customer projects and should lead to a constant improvement of cooling modules delivered to our customers. They also confirm and substantiate the current technological trends, i.e.:

- An increasing use of indirect cooling

- A willing to improving vehicle aerodynamics with controlled flaps at air entrance

- A strong necessity to adapt perfectly fan system efficiency to their operating points.

Novel loco cooling units: Guidelines on methodology, design and cost/benefits

We here cover three main issues: guidelines for future fan optimization, guidelines for future system optimization and cost/benefit analysis. It will be shown, that the ECOQUEST project considerably improved the methodologies and ECOQUEST results will be used extensively in future projects.

In the ECOQUEST project, we conducted system analysis, simulations of the benchmark system at full-scale and model scale, optimization of fan, guide vanes and diffuser, simulation of the optimized system at full-scale and model-scale, and instationary flow simulations. In future designs, some items might be spared. Especially the unsteady flow simulations have extremely high computational cost which is by no means reasonable from an economic point of view. Owing to increased trust in our methods, the full-scale simulations can potentially be spared as well because the differences between a simplified downscaled system and the non-simplified full-scale system turned out to be very small. This would in particular decrease the time for meshing and the computational cost. The remaining tasks to be performed would then be: development and simulation of a simplified and downscaled cooling module, assessment of the results, fan optimization taking installation effects into account, guide/vane diffuser optimization, integration of the new fan unit into the module and renewed system simulations, and construction of prototype cooling systems at model scale and aerodynamic/acoustic experiments.

The optimization conducted within the ECOQUEST project required much higher effort. Future optimization work will benefit from the following points:

- development of the general method is no longer required as it can be applied to arbitrary systems

- theoretical system analysis is existent in case the same cooling module type will be reused

- the optimization algorithms are fully developed and implemented such that they can be applied in arbitrary optimization work

- automated CFD loops are existent and just need to be modified for new tasks

- the relevant geometrical parameters for fan and guide vane optimization are now known such that from now on the first optimization loop should already lead to a good design

- the parameterized generation of geometry (required for CFD and CAD work) is existent and just needs to be scaled for other sizes

- drawings for the test rig are parameterized and can easily be adapted to other dimensions of the components

- the measuring equipment as well as scripts for evaluation of measuring data have been purchased/programmed and are suitable for any future designs

- there is an immense gain of experience of the people involved in the project

Potential impact:

Reduction of external and interior noise, also in view of compliance with legislation

In the past, technical progress made in noise reduction of vehicles was over-compensated by the growth of ground transportation. Given the predicted rate of traffic growth acceptable noise levels can be partly achieved through noise abatement measures (tunnels, barriers), but a substantial part of the reduction has to be achieved through reduction of the noise at source. For this reason the automotive and rail industry (worldwide as well as the European) has initiated a sustained research effort. The European road transport research advisory council (ERTRAC) sets 'noise reduction' as one of the major goals for future surface transport research: 'Noise levels (must be) appropriate to individual locations including quiet zones. ... The research challenge is to deliver low emissions while also meeting ... vehicle performance,....'

The European Rail Research Advisory Council (ERRRAC) identifies very similar future efforts: 'Simulation tools for noise assessment, the effectiveness of noise reduction measures .... are all areas for further study.... Deliverables include reduction in noise .... in addition to what will have been achieved through the FP6 projects SILENCE and QCITY.'

Thermodynamic principles require cooling systems for all present and future vehicle power trains. The stringent EU6 emission limits expected to come into effect in 2014 may require up to twice as high cooling power in road vehicles as compared to present technologies. Cooling systems are a major noise source, especially at standstill or stop and go traffic.

According to the latest European standards for interoperability of rail bound traffic within Europe the averaged sound pressure level LpAeq,T must not exceed 75 dB for both, electric power units and power units with internal combustion engines (EU 2005); ISO 3095 (CEN 2005). The research on noise prediction from mobile cooling units is widespread. Several groups in Europe are working on specific items to overcome the existing shortcomings and to extend the predictive methods to this complex application.

The ECOQUEST project overcomes the fragmentation of research in this particular field. Since all major players in Europe are participating, the project brings the critical mass together which guarantees major achievements in the development and industrial utilization of noise prediction tools for mobile cooling units. In terms of noise levels, the consortium partners agreed prior to the project that for the locomotive applications, gains of the order of 6-8 dB(A) could be achieved through the thermal management and acoustic optimization procedures, including passive noise control at the source, that are developed in the project. This target was fully achieved. In fact, even the fan optimization alone lead to an overall sound reduction of more than 7 dB. The sound attenuators showed an additional benefit by 1-2 dB. The assessment of the benefit due to the optimized thermal management is more difficult as it heavily depends on the operating conditions. Tests on a 23 km test track with a realistic driving profile revealed an average reduction by 4 dB with special benefits concerning maximum noise levels.

As for the automotive applications, which have been the subject of optimization for some time already, the consortium estimated a further reduction of 3-4 dB(A) prior to the project. Again, the target was fully achieved. In contrast to the locomotive, the sound attenuator played a more important role while the fan only contributed moderately.

Contribution to carbon dioxide (CO2) emissions reduction (or at least neutral impact to climate change)

Predicted traffic growth poses a significant hazard to achieving CO2 emission targets. Furthermore, the EU6 emission limits require up to twice as high cooling power in road vehicles as compared to present technologies. In the past, technical progress made in emission by the vehicles was over-compensated by the growth of ground transportation. Again, the European Road Transport Research Advisory Council (ERTRAC) sets 'low emission' as one of the major goals for future surface transport research: '...The research challenge is to deliver low emissions while also meeting ... vehicle performance, reduction in green house gas emissions and improvements in energy efficiency.' (ERTRAC, Strategic Research Agenda 2020). The European Rail Research Advisory Council (ERRAC) identifies very similar future research needs.

In ECOQUEST no technology was accepted which achieves noise reduction by adding weight or increasing energy consumption of the vehicle. Thus, the technologies aimed at are CO2 neutral or CO2 reducing. This was provided by introducing new simulation tools for optimization, novel noise reduction measures such as innovative fan designs with increased or neutral efficiency and micro-perforated components rather additional damping material.

Typically the combustion of 1 litre gasoline produces 2.38 kg of CO2, of diesel fuel 2.66 kg. For cars the latest EU-wide goal of CO2-emission of 120 g/km corresponds to 5.0 litre gasoline or 4.5 litre Diesel consumption per 100 km. As a rule of thumb 100 kg less vehicle weight reduces the fuel consumption by 1 litre per 100 km. Thus, decreasing the weight of an automotive cooling module by 2 kg yields an improvement in fuel consumption by 1%, i.e. a reduction of CO2 by 1.2 g/km. Although this does not seem a lot the automotive industry is putting tremendous effort on reducing weight of each component - even by the gram - which eventually sums up to a substantial weight reduction of the complete vehicle. In addition, an increase of efficiency of the electric or hydraulic fan (typical power consumption: 100 W to 1 kW), say by 5%, reduces the CO2-emission in the same order of magnitude. The actual result of the project is exactly in this range, see reports (especially D3.3, D3.6, D4.1).

The Diesel engine in a large locomotive is rated 3,600 kW, the maximum power required by the cooling fans is 270 kW. Typically the specific fuel consumption of the locomotive at full load is 191 - 195 g/kWh. The power required for operation depends very much on the load (weight of the train), the track and the climate. VTLT estimates that a reduction of the cooling fan power in a Voith loco by 10% may lead to an overall fuel saving of 1,300 kg, i.e. 3 tons less CO2-emissions per year. This target was considerably outperformed. The fan alone reduced the energy consumption by 20%. Together with the optimized cooling control strategy, the reduction amounts to almost 40%. According to the assumption above, the annual saving per locomotive will be 12 tons of CO2 per year instead of only 3 tons.

European competitiveness and economic impact

ECOQUEST provides the European automotive and train industry with demonstrated methods to reduce noise at source while increasing energy efficiency and reducing CO2 emissions. In doing so, it contributes to achieve European industries' objectives for greener vehicles to meet society's needs for more environmentally friendly ground transport of people and goods, and to enhance European global competitiveness. The economic impact of the ECOQUEST programme on the European ground transport sector will derive not only from increasing European competitiveness but also from contributing to the removal of a potential limit on the natural growth of the sector worldwide.

Recent research in the USA and Japan has established a lead in some of the technology areas being considered. The work proposed in ECOQUEST will at least re-establish parity in those areas whilst moving ahead across energy saving and CO2 emission reduction concepts.

ECOQUEST is an essential element in ensuring that ground traffic can grow in harmony with other modes of transport. It has to be assumed that any restriction of this growth due to inability to meet noise and CO2 emission targets will have a detrimental effect on European businesses which would otherwise be using air transport for freight or passengers. Moreover, the development of innovative modeling approaches and their implementation in sophisticated software tools is meant to enhance system assessment and facilitate decision-making in ground transportation, but also in other applications of economical relevance such as

- heating, ventilating and air-conditioning systems for any transportation (including aerospace), residences and factories;

- cooling systems for electronic devices, that present strong similarities with the ECOQUEST applications regarding cluttered environments: laptops for example;

- energy processes, being not necessarily confined but that show very similar broadband noise issues such as wind turbines.

Finally, it must be anticipated that the future of ground transportation will involve a growing fraction of electrically-powered trains and hybrid automotive propulsion as well. It is nowadays acknowledged that whichever hybrid technology becomes predominant in the future (fuel cells, etc.), the controlling electronics and power transformation will require sophisticated cooling management, with two very strong challenges to be faced. Firstly, in the absence of an internal combustion engine running, the cooling system will become the dominant sound source for low-to-medium rolling speeds. Secondly, energy intensity and storage being key factors in these hybrid technologies, the energy efficiency of the cooling system will become determinant for the overall viability of the system. ECOQUEST anticipates on these needs by addressing altogether thermal efficiency and acoustic performance of the cooling system.

Education

The consortium includes 4 renowned European Universities and Research Centres, i.e. nearly one half of the total partnership, a situation which is highly beneficial to training and education. For undergraduate, post-graduate and PhD students, the participation to such programs is a unique opportunity: the research performed is of high quality due to the expertise accumulated in the consortium, the concentration of financial resources and the innovative scientific route which ECOQUEST develops i.e. new flow control concepts. It also provides exposure to a multicultural environment and to establish international relationships that are useful to build and strengthen the European Research Area.

As users, developers and suppliers of advanced innovative technologies, automotive and locomotive/train manufacturer know the value and importance of continuously developing human skills, contributing to the European objective of moving toward a knowledge-based society. The partnership brings students and scientists an excellent opportunity to gain experience in the European scientific community in the field of engineering. Giving education a high priority ensures the long-term supply of first-class, well-trained and suitably qualified engineers and scientists.

The integration of PhD students into the project team lead to the successful completion of at least two PhD thesis's, two being still in progress. In addition, numerous students were involved as research assistants in the project who gained exceptional experience in international research.

Dissemination

Dissemination was one of the major concerns throughout the project which can in particular be observed in the Tables A1 and A2. There was a strong focus on publication in journals 5 contributions) and on conferences/workshops (39 contributions), all listed in Table A1 and A2. Among the publications there are also two PhD thesis's which are based on work within ECOQUEST. Two further PhD thesis's shall be finished soon. Besides, there have been some other events where we presented our project and its outcomes. The two most important events were a three days lecture series and a contribution to the InnoTrans Exposition 2012.

The three days lecture series was held at von Karman Institute for Fluid Dynamics April 22nd-24th entitled "Modeling, measurement and control of ventilation and cooling fan noise". The first two days were used for general lectures about acoustics which partly covered novel ECOQUEST outcomes. The last day was an ECOQUEST workshop in which we exclusively reported about project results. All lecturers belong to the consortium. Lecture notes were created for each contribution and distributed among the participants.

Main lecture series

Title Lecturer Affiliation

Fundamentals of aeroacoustic analogies C. Schram VKI

Linearized methods for broadband fan noise M. Roger ECL

Multiport education for ducted components M. Abom KTH

Noise control in ducts M. Abom KTH

Boundary Element Methods for fan noise scattering M. Tournour LMS

Innovative passive control of cooling fan noise M. Abom KTH

Innovative blade design K. Bamberger USI

Heat exchanger modeling M. Abom KTH

ECOQUEST workshop

Title Lecturer Affiliation

Efficient prediction of acoustic installation effects M. Roger ECL

Aeroacoustic modeling and validation of generic locomotive cooling unit C. Schram VKI

Aeroacoustic and thermal optimization of automotive cooling system M. Henner VAL

Advanced passive noise control using micro-perforates M. Abom KTH

The contribution to the InnoTrans 2012 was mainly organized by VTA with support from USI. The exposition took place in Berlin, Germany, from September 18th until 21st. InnoTrans is the most important world-wide exposition for the railway industry. In 2012, around 126,000 professional visitors and 20,000 public visitors came to see the stands of more than 2,500 exhibitors from 49 countries. One booklet at the VTA stand was exclusively dedicated to our ECOQUEST project and presents our major achievements concerning locomotive cooling. The EC funding was acknowledged. The booklet was explained and handed out to interested visitors and is also publicly available in the internet:

http://www.voithturbo.com/applications/vt-publications/downloads/1962_e_2012-07-31-g2283-ECOQUEST_e_screen.pdf

Commercial exploitation in automotive industry

This summary describes benefits of the mains innovations that have been considered during the ECOQUEST project. A brief technical presentation highlights main advances offered by the systems studied. Potential gains in terms of reducing CO2 emissions are presented for the new technologies. Assessments on the market penetration and on the automotive growth are presented to figure out future impacts of the innovations proposed for the thermal management.

Traditional systems for thermal management are constituted by two loops, dedicated respectively to engine cooling and climate control (heating, cooling, defrosting, demisting). Thermal exchanges with the exterior are made on the front end, which is equipped with a cooling module. Among the various heat exchangers, one can find the radiator (engine cooling), the Charge Air Cooler (engine air entrance), the condenser (refrigerant loop) and sometimes an oil cooler (transmission, driving assistance and/or gear box).

The concept that equips the ECOQUEST test vehicle has been designed to minimize the total thermal power, previously distributed on three separate loops, and now shared on two simplified loops. It proposes different thermal exchangers for each function that are indirectly cooled by only two loops. High and low temperature loops are used for the Water Condenser (WCDS), the Water Charge Air Cooler (WCAC), eventually by the Water Oil Cooler (WOC), the Water cooling for Exaust Gaz Recirculation and of course for the engine cooling.

Cooling components are no longer designed for the maximum use of each function, and the architecture optimizes the overall performance to the just needed. The main benefit comes from the sizing of heat exchangers to the just needed thermal performance. All components are not used at their peak level at the same time.

The cooling module architecture that has been redesigned with the Ultimate CoolingTM architecture yields to some aerodynamic effects that have been investigated during the ECOQUEST project. In particular it is found that the cooling module has a lower porosity, which leads to the benefit of a reduced vehicle drag. This is explained by the decrease in airflow under the hood, causing less friction and losses. This favorable effect is counter-balanced by the higher load which is imposed on the fan system: at low vehicle speed, the natural flow is insufficient and must be forced by ventilation. It appears that the design of the module and its coverage by one or two fans becomes an important criterion for the effectiveness of the concept. The combination of the two effects (less drag, more fan power) is however favorable to the concept UC showing gains on the fan system power of around half a gram of CO_2 per kilometer.

This concept brings also some modularity in its architecture since additional functions can be easily added (or removed) on the water circuit. Additional cooling is organized for battery, electronics and electrical motor. The heat exchangers are furthermore optimized to perform the cooling at the closest location of the component to be cooled. It allows standardization and a simplification in the management of the different versions across of powertrain across platform. For hybrid vehicles, the battery, electronics and electrical motor are cooled by the same coolant liquid, via the low temperature loop.

In terms of fan system sales, Valeo has the ambition to increase its market penetration from 8 to 11 %, and following the global market growth worldwide it is expected to increase sales by 50% between 2010 and 2023. This aim could be achieved if Valeo maintains its expertise on this product by applying methodologies for aerodynamic optimization and acoustic level minimization. The growth produced by this increase in market share represents a global amount of 500 millions of Euros.

The total Charge Air Cooler market for Valeo is expected to increase from 18 to 48 millions of units between 2010 and 2023. The sharing between direct technology (CAC) and indirect technology (WCAC) will evolve in the same time, the WCAC rising from 3% to 33% of penetration.

Commercial exploitation in locomotive industry (1): Technical and methodical achievements

The exploitation plan is discussed with respect to three major fields which will be described separately.

Fan optimization

The team carried out fundamental systems analyses as well as CFD simulations and acoustic experiments with mock-up units. The following insights were gained:

- Reduction of the fan diameter smoothes the speed profile at the fan inlet and thus decreases leading edge noise.

- Further noise reduction is achieved by optimized blade profile and improved blade sections ('sickles'), which also increases efficiency.

- The highest energetic saving potential lies in the reduction of the exit losses through guide vanes and diffusers. The solution combines both components in one compact unit. Optimum aerodynamic design was achieved through CFD simulations and an optimization algorithm. The geometry thus achieved differs from conventional designs and excels by higher efficiency.

- Homogenization of the exit flow decreases losses and compensates anticipated drawbacks due to the smaller fan diameter.

Improvements achieved:

- Cooling capacity increased by approx. 10 %

- Energy consumption decreased by approx. 20 %

- Broadband noise levels decrease by approx. 6 dB

- Specific level at blade-passing frequency reduced by more than 10 dB

System optimization

The energy consumption and the noise emissions of cooling systems not only depend on the fan design but also on the interaction of all systems components such as cooling unit, vehicle and environment. Apart from the aerodynamic fan, the cooling system used for this study also includes the hydraulic systems, the hydrostatic drive with associated peripherals, as well as the control systems with relevant geometric and physical parameters. The model for the complete vehicle-rail system is divided into various sub-models (e.g. diesel engine, hydrodynamic transmission, vehicle, driver, track profile), which characterize the system's behavior and the interaction with the entire vehicle. By coupling the vehicle model with the cooling system, the entire system can be examined. The following variations were applied:

- Fundamental design studies and detailed component optimization

- Control strategy e.g. of fan regulation

- Operating circuit and ambient conditions

Depending on the ambient temperature, significant energy saving and noise reductions can be achieved. Minimum noise emissions can be realized by modified control strategies for the reduction of the dynamic fan speed. Minimum noise emissions can be achieved by modified control strategies for the reduction of the dynamic fan speed. In combination with a load balancing mechanism between the various water circuits and the cooling system, the operating load of both circuits can be adapted to the same level, which allows significant energy savings.

- Energy savings of up to 50 %

- Noise reduction of up to 3 dB(A) just by system optimization

Sound attenuator design

Sound absorption systems have proven themselves in cooling systems as acoustically effective, passive sound dampers. 'Passive' in this context means that no additional energy is required for sound absorption. The aim is to reduce noise effectively by simple and space saving measures without modifying the aerodynamic operating point of the fan. For this purpose, the cooling grid of the prototype locomotive was temporarily installed with sound damping elements to allow measurements. With new locomotives, the two functions 'protection' and 'sound absorption' have to be constructively combined in the vehicle.

VTA achieved the aim of reducing the energy consumption and noise emissions with the outcomes of the ECOQUEST project. Depending on the requirements of the customer, the energy saving and noise reduction outcomes can be integrated in future cooling system designs.

Commercial exploitation in locomotive industry (2): Cost-benefit analysis

A TecRec is a UIC/UNIFE standard designed to be used within the European region. This document provides a voluntary standard on the 'Specification and verification of energy consumption for railway rolling stock' for use by companies in the rail sector if they so choose. The document is set out in the same format than EN standards including, where appropriate, normative and informative annexes. This is so as to facilitate the interface with the ENs.

The freight mainline profile over 300 km includes three planned stops plus two stops in front of red signals. Two third of the line is horizontal track whereas the middle part includes a mountain passage. This reflects the fact that long distance freight train operation includes railway lines with significant gradients in many countries, not only through the Alps. The gradients of the profile are selected in such a way that a four-axle locomotive can haul the same train as the reference train with average mass as specified below. Although locomotives and wagons of many freight trains may be capable to run faster than 100 km/h, the profile is limited to 100 km/h, which is the maximum speed for most loaded freight trains according to lines and wagons of Class D (22.5 t axle load). Timetable requirements have to be interpreted in the same way as for intercity passenger traffic. Train and timetable are applicable for electric trains or fast freight DMUs only. Trains hauled by diesel locomotives can not hold the timetable for the mountain section, unless they have an uneconomically high number of locomotives.

The system performance with the validated system simulation model of the complete locomotive is investigated for the freight mainline profile.

The results are input for the live cycle cost investigation. The main quantifiable LCC argument is the achieved fuel consumption saving within the ECOQUEST developments. With the cooling system cost (Funding cost and maintenance cost excluded) the amortization time can be investigate. Therefore standard values for operation hour, fuel price and fuel price escalation is assumed. The costs are based on manufacturing costs (standard parts and additional components) and development cost (Based on a batch size of 20 cooling units).

Altogether, VTA achieved the aim of reducing the energy consumption and noise emissions with the outcomes of the ECOQUEST project. Therefore the consortium develops new methods and components for rail applications. A huge emission reduction 51 g/km and noise reduction up to 7 dB(A) can be achieved. The most designs can be implemented in future cooling modules with attractive cost/benefit ratio. The current international or local noise standard does not necessitate the immediate realization of all ECOQUEST outcomes. Major standard specified no usual operation point of the cooling module. Therefore the fan isn't running during certification measurement. Moreover, the real operation cycle doesn't consider in the certification process. On the other hand the fuel consumption saving can become to a commercial issue to implement the ECOQUEST outcomes.

Commercial exploitation in simulation industry

During ECOQUEST, LMS with other partners has investigated a new technique for broadband fan noise radiation and scattering. The approach proved to be quite accurate for a number of well-defined and control test cases.

The scattering part is based on the computation of transfer vectors (or transfer function) which can be computed using any PDE methods such as Boundary Elements and Finite Elements. Not only this allows to apply the methods to FEM (combined to Perfectly Matched Layer for open domains) but also makes it easier to apply to BEM techniques such as Fast Multipole BEM or H-Matrix.

It is therefore expected that the approach will be commercialized in the LMS Virtual.Lab aero-acoustic solution. Nevertheless, the approach did not prove to be convincing on the VALEO test case and some further investigation and tuning are unfortunately needed. It is expected that the new approach will open doors to new applications and will allow to better iterate on the design refinement.

List of websites:

http://www.uni-siegen.de/ECOQUEST/

Related information

Result In Brief	• Helping transport keep their cool
Documents and Publications	• Final Report - ECOQUEST (Efficient Cooling Systems for Quieter Surface Transport)

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