Final report

1.1 Project details

Project title	Gas Engine Methane Exhaust Reduction by Catalyst
Project identification (program abbrev. and file)	ForskEL project no. 2011-1-10699
Name of the programme which has funded the project	PSO R&D Programme ForskEL
Project managing company/institution (name and address)	Danish Gas Technology Centre (DGC) Dr. Neergaards Vej 5B 2970 Hørsholm DK - Denmark
Project partners	Smart Muffler Corporation (SMC) Alastair Ross Technology Center #496 3553 – 31st Street NW Calgary, AB T2L 2K7 Canada
CVR (central business register)	12 10 50 45
Date for submission	11.04.2016

1.2 Short description of project objective and results

Danish Gas Technology Centre (DGC) has decided to recommend a prematurely termination of the project due to a number of technical and financial problems and challenges leading to a heavily delayed project time schedule. Lack of progress and very low expectations to the chance of achieving the objectives of the project within a reasonable time frame made for that decision.

This final report describes the results obtained and the events leading to the decision of terminating the project.

Dansk Gasteknisk Center (DGC) har besluttet at anbefale en nedlukning af projektet før tid på grund af en række tekniske og økonomiske problemer og udfordringer, som har ført til en stærkt forsinket tidsplan. Manglende fremskridt og meget lave forventninger til chancen for at nå målene for projektet inden for en rimelig tidsramme ligger til baggrund for denne beslutning.

Denne endelige rapport beskriver de opnåede resultater og de begivenheder, der førte til beslutningen om af nedlukning af projektet.

1.2.1 English summary

The aim of this project is to demonstrate a technology for reducing methane emission from natural gas fired IC gas engines. The objective is to:

- Demonstrate the process "Reverse-Flow Catalytic Conversion" of methane on a full-scale 1 MWe CHP plant (hereafter named RFC)

- Document long term efficiency of the process regarding methane conversion
- Investigate the influence of the process on other key emission components (NOx, CO, formaldehyde) as well as the overall and electrical efficiency of the CHP plant
- Evaluate economics of the reduction technique through capital and operational costs

The mechanical engineering phase is completed with the Smart Muffler v4.1 design as the final step close to ready for manufacturing. Extensive modeling work has been performed by Smart Muffler Corporation (SMC). The work is documented in memos and reports. Tasks regarding the electrical system are yet to be completed.

The manufacturing phase is started with engagement of component suppliers including preliminary discussions of CRD and NDA agreements. Sample of catalytic material has been procured and send for testing against Sulphur values.

1.2.2 Danish Summary

Dette projekt omhandler en ny teknologi til reduktion af metan emission fra naturgasfyrede stationære gasmotorer på decentrale kraftvarmeværker. Formålet med projektet er at:

- Demonstrere processen "Reverse-Flow Catalytic Conversion" af metan på fuld skala 1 MWe kraftvarmeanlæg
- Dokumentere processens langsigtede effektivitet med hensyn til konvertering metan
- Undersøge processens indflydelse på andre centrale emission komponenter (NOx, CO, formaldehyd) samt den overordnede og el- og varmevirkningsgrad af kraftvarmeværket
- Vurdere økonomi, miljø og teknologi

Det mekaniske design og projektering af katalysatorenheden er afsluttet med Smart Muffler v4.1 som det sidste trin i en udviklingsrække. Konstruktionen er tæt på at være klar til produktion. Der er udarbejdet omfattende modelberegninger, som er dokumenteret i notater og rapporter. Der udestår stadig opgaver vedrørende det elektriske system.

Fremstillingsfasen er startet med aftaler med komponentleverandører, herunder foreløbige drøftelser af CRD og NDA aftaler. Prøve af katalysator er blevet indkøbt og sendt til test hos leverandøren for håndtering af svovlindhold i naturgassen.

1.3 Executive summary

1.3.1 Background

Methane is a significant greenhouse gas contributing to global warming. In Denmark natural-gas fired gas engines are responsible for 91 % of the total methane emission from the de-centralized CHP plants (2006 figures), although they are only responsible for 35 % of the total fuel consumption in the sector.

Until now it has been proven difficult to effectively reduce the methane emission from natural gas fired CHP plant engines in a technical and financially attractive way. Several projects have investigated catalytic reduction of UHC. The main problem with this technique is the relatively fast deactivation of the catalyst. Furthermore catalytic conversion of methane is more difficult compared to conversion of CO and other hydrocarbons and demands higher operating temperatures. That's why the low exhaust temperature of lean-burn gas engines poses a problem, especially if the catalyst has deactivated to some degree.

A Canadian company, Smart Muffler Corporation (SMC), has developed a concept for catalytic treatment of exhaust gas from internal reciprocating engines. The reactor is a passive ceramic oxidation catalyst with platinum loading buffered by dummy ceramic elements. The process was originally developed during the 90's for natural-gas powered diesel dual-fuel systems, which are mainly powered by natural gas and ignited by diesel pilot oil. The method is described as "Compact Reverse-Flow Catalytic Conversion" (RFC) and deals with issues as low exhaust gas temperature during low to medium load operation of the engine.

The purpose of this project was to demonstrate the RFC technology on a Danish 1 MWe natural gas fired CHP plant.

1.3.2 Main activities

The main activities in the project are summarized in the bullets below:

- Preparing a Consortium Agreement
- Kick-off meeting in Calgary, Canada
- Design and modelling work on catalyst methane conversion performance and mechanical structures
- Optimisation of the RFC unit to accommodate pressure drop limitations set by engine specifications at the plant host
- Discussion with sub-contractors/suppliers (catalyst, valves, piping, control system, electrical harness etc.)
- Change of plant host for testing the RFC unit
- Pressure measurements on gas engine flue gas system
- Documenting distances between gas engine and surrounding installations
- Design work regarding implementation of the RFC unit in flue gas system of the gas engine
- Re-evaluation and status of the project after the death Mr. Ed Mirosh, February 2013 (Mr. Mirosh was the owner and founder of SMC and also one of the original creators of the project)
- Manufacturing phase tasks i.e. agreements, testing and production
- Project on stand-by while SMC was searching for new financing

The first activity performed was to prepare a Consortium Agreement to be signed by the partners. By request of SMC the agreement included a Confidentiality and Non-Disclosure Agreement (NDA). This activity was more time consuming than expected and was the one of the reasons for the initial application for extension of the project filed January 2012. The Consortium Agreement and Non-Disclosure Agreement were signed by all parties at the end of October 2011.

During the last months of 2011 and 2012 SMC performed extensive designing and redesigning work aiming to comply with the engine requirements to maximum back pressure in the

exhaust system. This emphasis included building several main models in the modelling software to simulate pressure drop. In order to facilitate the implementation of the demonstration catalyst the engine manufacturer were contacted for a dispensation to operate the engine at a higher back pressure than normally allowed, unfortunately without permission. Difficulties in complying with the requirements to maximum exhaust back pressure led to the change of plant host in the beginning of 2013 as well as changing valve design.

February 2013 the founder and co-creator of the project, Ed Mirosh SMC, passed away. This led to a setback in the development work but at the end of 2013 a Generation 4.1 of the RFC was developed. This unit meets the pressure drop requirement s as well as the installation dimension requirements set by the new plant host Dronninglund Fjernvarme.

During 2014 and the first half of 2015 SMC has been working on securing capital for future operation and a reconstruction of the company which implied initiation of an evaluation of the developed technique performed by a third part company.

1.3.3 Main results

At the time of the release of this final report no physical results of the project have been achieved. The result of the work performed is materialized in the interim reports, memos and reports prepared by DGC and SMC during the project.

Four reports have been prepared by SMC documenting the company's work:

1. Mirosh, Ed; Pressure drop simulation report for 1 MW engine exhaust system; Released January 11, 2013.
2. Yuan, James and Mirosh, Jason; Pressure drop optimization and simulation report; Released May 1, 2013.
3. Yuan, James and Mirosh, Jason; Bended pipe report; Released July 1, 2013.
4. Mirosh, Jason; Year end report; Released January 6, 2014.

The main result is a fully designed and engineered "Reverse-Flow Catalytic Conversion" demonstration unit ready for manufacturing phase. The demonstration catalyst unit consists of the following main components:

- Piping and cone dimension transitions
- Valves and actuators
- Ceramic monolith and catalyst material
- ECU and wiring harness

Figure 1 and Figure 2 show examples of the final RFC unit designed and engineered for a Caterpillar G3516 natural gas engine at Dronninglund Fjernvarme. The mechanical as well as the flow and pressure related parts of the construction are thoroughly optimized.

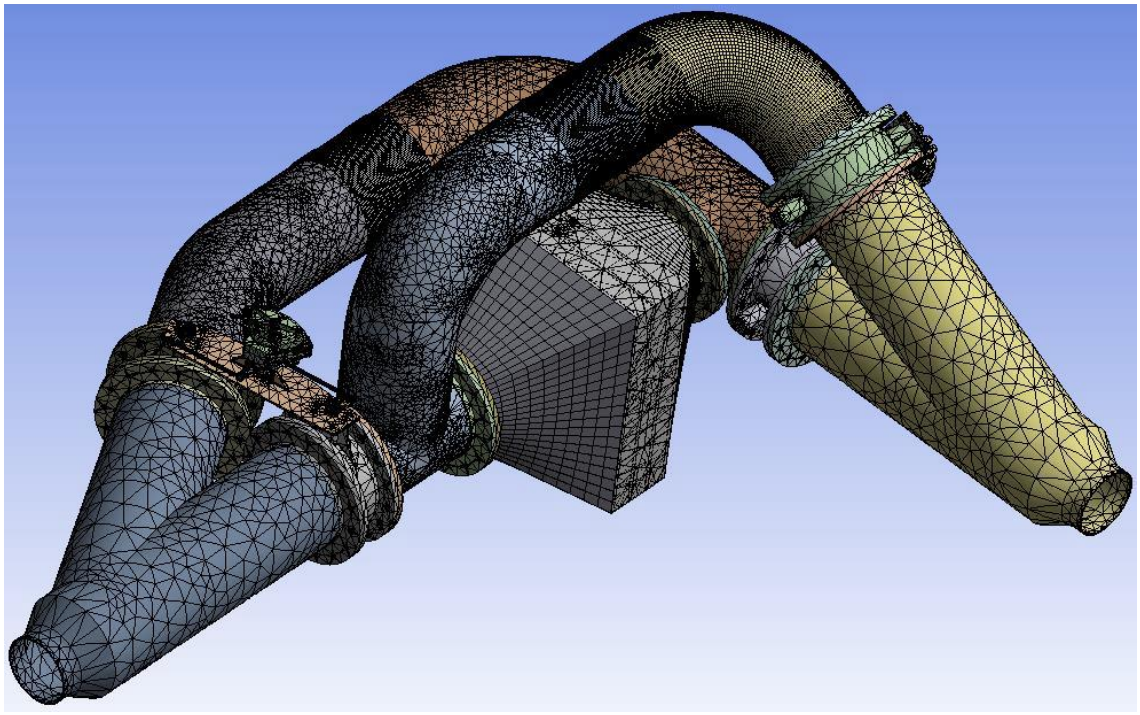

Figure 1 Assembly Meshing. Modeling software computes the pressure differentials over the entire system using the meshing settings. The RFC is accurately optimized for pressure.

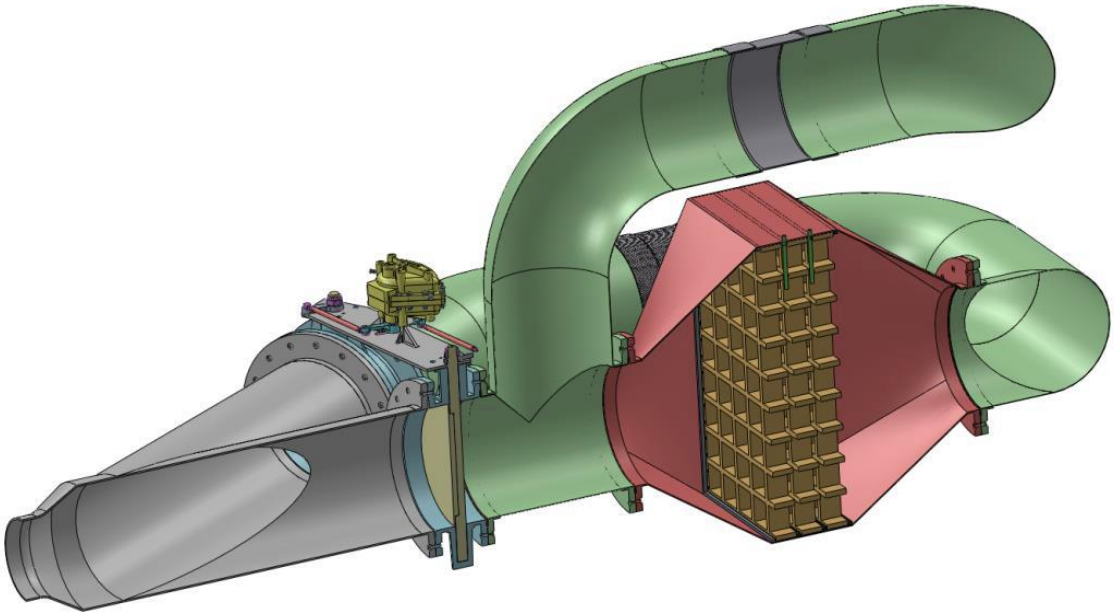

Figure 2 Section View of Ceramic Monolith and Cone

1.4 Project objectives

This project is a demonstration project aiming to document a catalytic methane reduction technique on full-scale basis on a natural gas fired CHP plant. The technique, which haven't been demonstrated on stationary natural gas fired lean-burn engines before, is developed by a Canadian company, Smart Muffler Corporation (SMC), and does not suffer from previously encountered problems like deactivation of the catalyst after a shorter operation period. High methane conversion rates about 90 % are expected.

The objective of this project is to:

- Demonstrate the process "Reverse-Flow Catalytic Conversion" of methane on a full-scale 1 MWe CHP plant
- Document long-term efficiency of the process regarding methane conversion
- Investigate the influence of the process on other key emission components (NOx, CO, formaldehyde) as well as the overall and electrical efficiency of the CHP plant
- Evaluate economics of the reduction technique through capital and operational costs

The major risk associated with the project was, from the beginning, the possibility of just another catalyst project suffering from poor efficiency and fast deactivation of the catalyst. Furthermore development and demonstration projects often, by experience, are associated with difficulties time schedule wise.

Secondly the building and manufacturing a component for the first time will almost for sure imply unforeseen problems.

Third: Some start up hassles could be expected due to the long distance between the project partners.

From the beginning the project didn't evolve according to the time schedule. Preparing a cooperative agreement, the consortium agreement, turned out to be more time consuming than expected. Annex 1 indicates how the project evolved with respect to the originally time schedule laid out in the application.

In order to initiate the project properly and balance expectations between the partners DGC tried to set up a kick off meeting in Denmark at the original plant host Nørager Varmeværk. However after several cancelations from SMC a meeting was set up in Calgary December 7, 2011. That was eight months after project start. At that time SMC had already performed some work, but had not accounted for the actual physical surroundings at the CHP plant nor had they taking into account the back pressure limitations given by the gas engine at the plant.

After the meeting in Calgary the work concentrated on overcoming the back pressure limitations given by the gas engine while respecting the physical dimensions at the plant. Also

The the death of Ed Mirosh, SMC, February 2013 was a sad event that affected the development of the project.

Overall the project is still, after four years, situated at WP1, the design and production work package.

1.5 Project results and dissemination of results

The technique of the RFC is a constantly reversing of the exhaust gas flow from the gas engine through a catalytic monolith, and thereby it is possible to highly elevate the centre temperature of the monolith maintaining the boundary temperatures approximately at exhaust gas temperature level. SMC documented high methane conversion at low exhaust temperature without utilizing external heating sources such as injection of surplus fuel in the upstream the catalyst. Also, at high loads CH4 conversion was enhanced due to a constant higher temperature level in the catalytic monolith.

Test results showed CO and reactive hydrocarbon conversion above 95 % and CH4 conversion around 90 % for most operating conditions.

Some of the first reported activities performed by SMC were simulating and optimizing methane destruction rates under different RFC operating conditions.

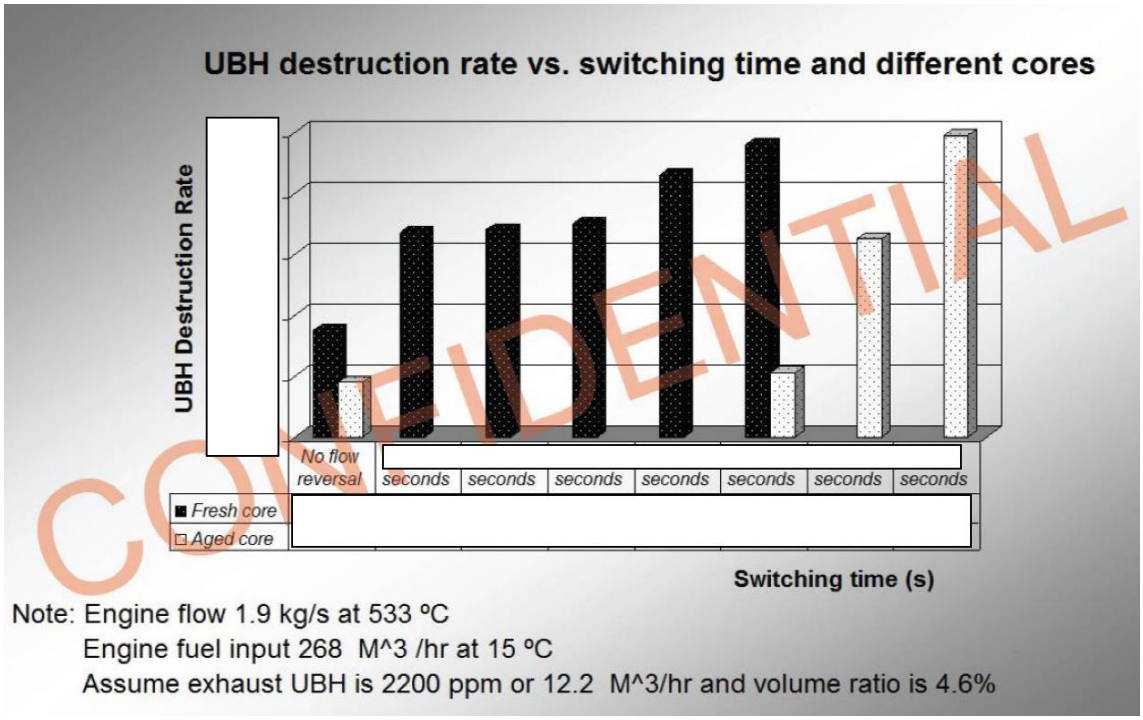

Figure 3 Example of methane destruction rates simulation results (information details partly covered due to confidentiality reasons)

One of the first versions of the RFC unit is shown in Figure 4. The construction is characterized by an unsymmetrical lay out and the flow direction of the exhaust gas through the catalyst is controlled by a single valve block containing plug valves. Pressure drop is unevenly distributed with respect to flow direction.

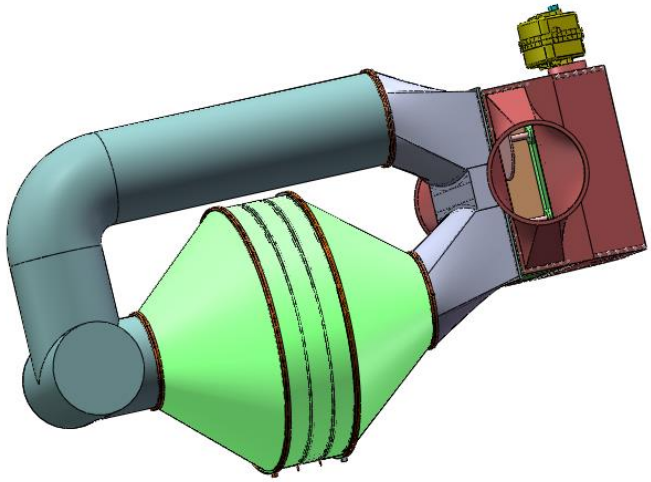

Figure 4 One of the first lay outs of the RFC unit

This RFC were meant for installation at Nørager Varmeværk to be incorporated at the Tedom unit as seen in Figure 5. This unit is very compact and the casing makes it more challenging to design a retrofit catalyst unit that can be accommodated in the existing system.

Because the exhaust gas is divided into two separate gas streams SMC changed the RFC design into two dedicated catalyst units which should imply less back pressure in the exhaust system.

Figure 5 One of the two Tedom/Caterpillar units at Nørager Varmeværk

The Danish Caterpillar representative, Pon Power, was contacted in hope for a dispensation to operate the gas engine at higher back pressure levels than normally allowed. Pon Power contacted Caterpilar US (service request CAT-327998-VNN0) with the DGC enquiry:

> *Danish Gas Technology Centre a/s is the manager of a public funded project demonstrating a full scale process capable of reducing air emissions from natural gas engines in combined heat and power plants. The test is planned for a period of 6000 operation hours which equals approx. 3 years (The engines in the Danish CHP market are characterized by quite low annual operating hours due to low prices on electricity). Accord-*

ing to our information the maximum allowable exhaust system backpressure is 670 mm H2O for the G3516 engine. However it will be desirable for the project to extend the upper limit to 1.5 PSI (1055 mm H2O). We are aware, that fuel consumption probably will increase, but this is a minor issue with respect to the test objectives. Is there issues regarding operation safety, reduced lifetime, increased service etc. linked to operation at a higher backpressure up to 1055 mm H2O measured downstream the Turbo Charger for the Caterpillar G3516 gas engine? Will operation at this higher backpressure cause increased stress on specific components? What is Caterpillar's opinion on this request?

Caterpillar's answer was negative:

> *Increased back pressure can drastically reduce the performance of the engine such as low power and increase in fuel consumption. It can also shorten turbo life and exhaust valve life as well. I recommend you follow the A&I guide LEBW4970 for exhaust back pressure. Regards Dan Loughry*

At the end of 2012 it was decided to change for a new plant host which could offer better conditions for installing a RFC demonstration unit. November 2012 Dronninglund Fjernvarme agreed to host the demonstration project.

The physical surroundings in the engine room at Dronninglund Fjernvarme is much more spacious and the engines are not installed in casings as were at Nørager Varmeværk.

Figure 6 Gas engines at Dronninglund Fjernvarme

During 2013 a lot of work was performed. The dimensions of plant were documented, pressure drop measuring was carried out and several iterations of the RFC were developed.

In order to decrease back pressure further SMC changed the design of the valve lay out from plug valves in at block construction to butterfly valves inserted in the piping.

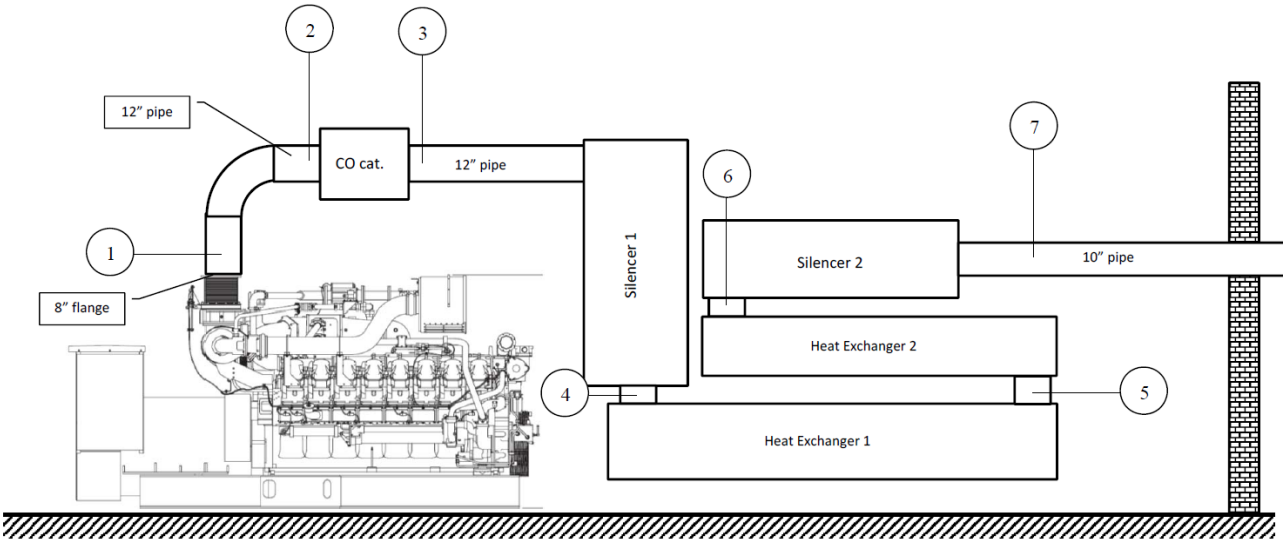

Figure 7 Sample points dedicated for measuring pressure drop and back pressure

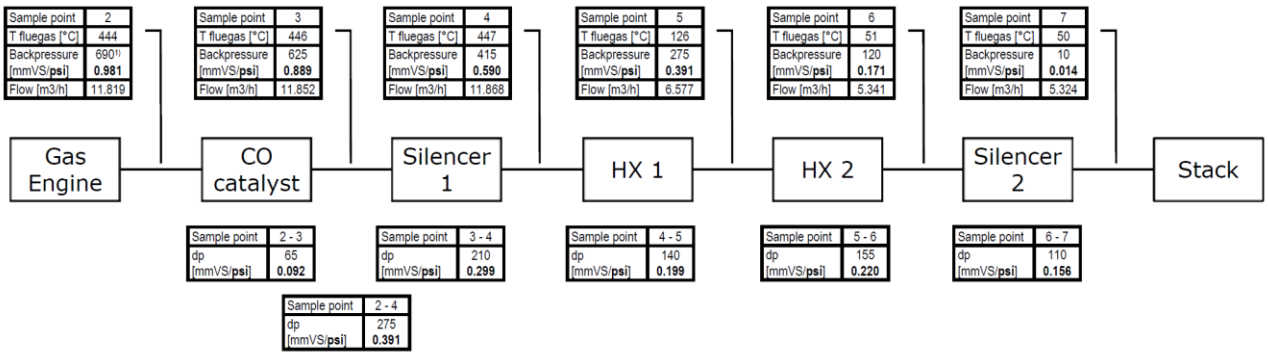

Figure 8 Results of measuring pressure drop and back pressure at engine #3

By agreement with the operator at Dronninglund Fjernvarme the project was allowed to remove existing CO catalyst and silencer 1 while the demonstration project was running. This would free up space for the incorporation of the RFC as well as back pressure headroom. The RFC unit would act as both silencer and CO catalyst. To speed up the process of getting the RFC unit into the manufacturing phase and installed at the plant DGC suggested adding a flue gas fan in order to overcome the still ongoing back pressure issue. See Figure 9. This solution however was not taking further into consideration.

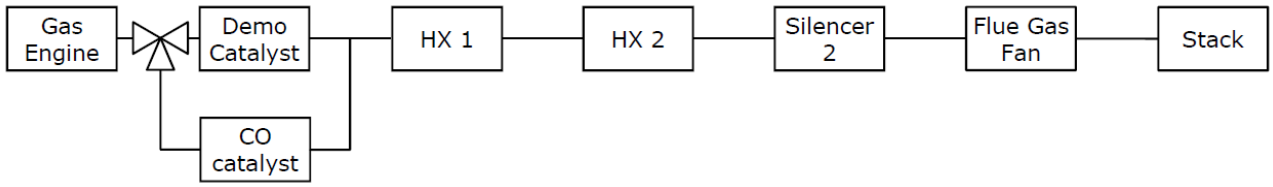

Figure 9 System layout proposal including Smart Muffler RFC catalyst and flue gas fan

On basis of detailed measuring of distances to other engines, equipment and building structures DGC provided SMC with information of available space for accommodating the RFC.

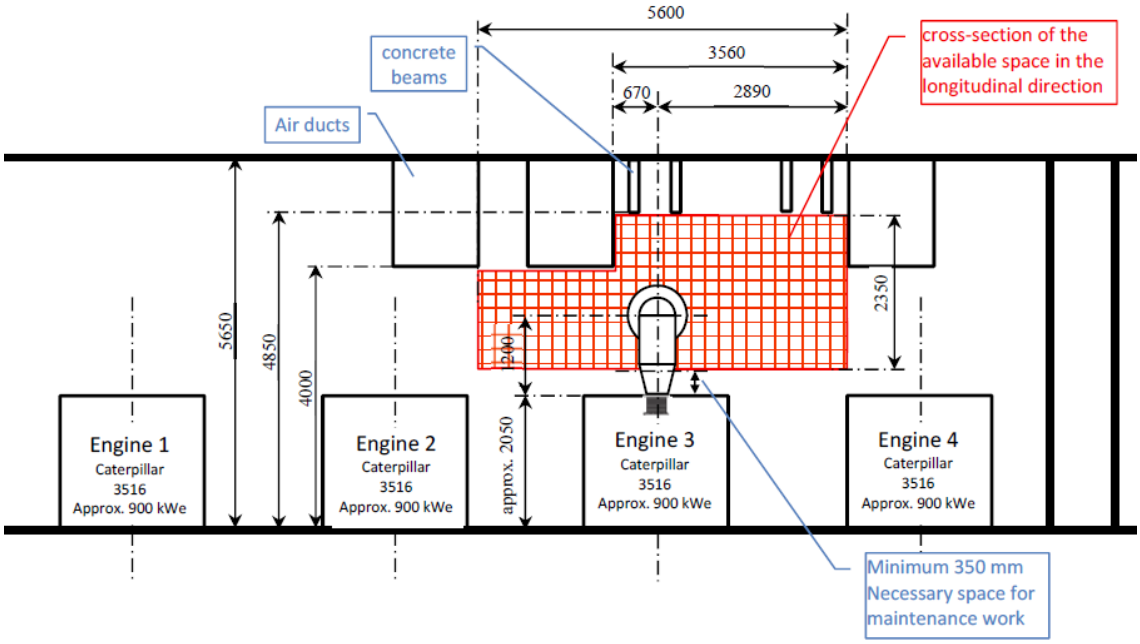

Figure 10 Dronninglund District Heating Plant, Engine room layout - Cross-sectional view

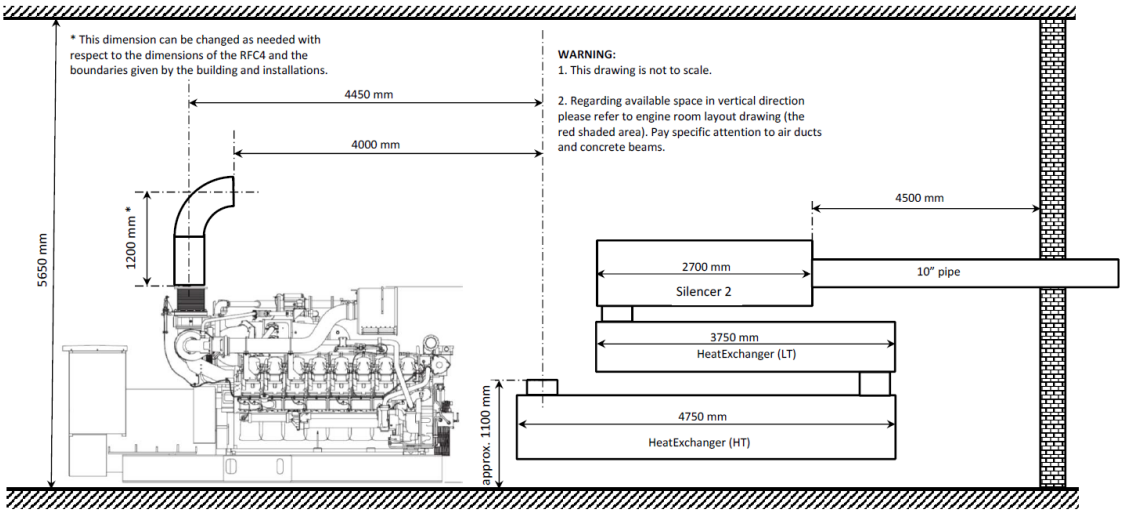

Figure 11 Dronninglund District Heating Plant, Caterpillar 3516 engine layout, Side view

During the summer of 2013 the overall dimensions of the RFC was decided, see Figure 12 and Figure 13.

SMC did some further optimization and investigation of the catalyst with respect to the gas composition from the engine. January 2014 SMC issues the "Year End Report" covering 2013 in which they describe the financial problems and search for new capital and the need for reconstruction of the SMC company.

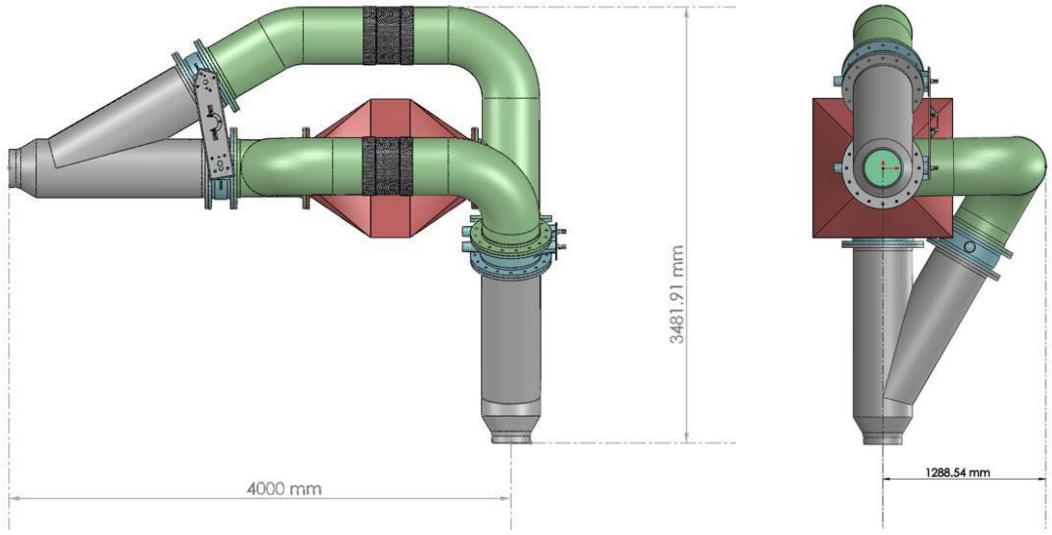

Figure 12 Dronninglund District Heating Plant, Caterpillar 3516 engine layout, Side view

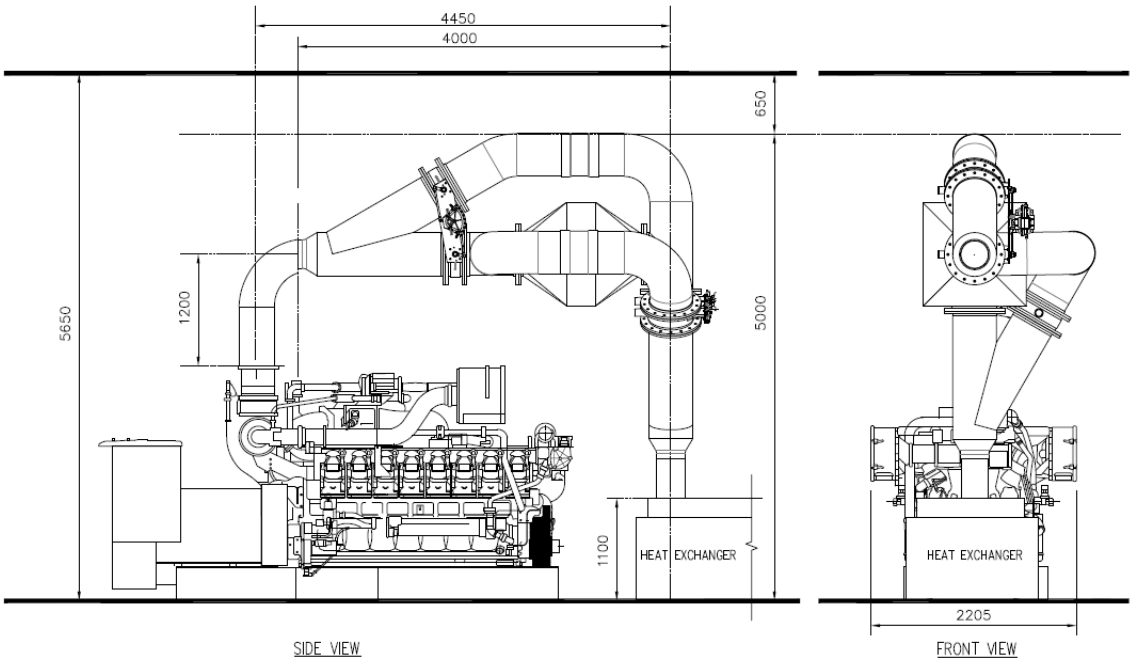

Figure 13 Dronninglund District Heating Plant, Caterpillar 3516 engine layout, Side view

Because the RFC demonstration catalyst never proceeded to the manufacturing phase, the main objective of the project i.e. demonstrating and documenting the methane destruction process never succeeded. One of the reasons is the struggles of incorporating the catalyst in the exhaust system with respect to the back pressure limitations. This issue was never addressed in detail during the creation of the application and in the early work of the project.

The results of the project are not disseminated in any way except for the Energinet.dk reporting. For confidentiality reasons a lot of the results, reports, simulations etc. must be discussed in terms of to which degree they can be distributed.

At the time of preparation of this report SMC has consumed 90 % of their PSO funding but have acknowledged their obligations to the project.

1.6 Utilization of project results

Utilization of the project results will likely be very limited in the Danish market. First of all there are no measurement results to document the process and utilization of the design and engineering results achieved by now will require a continuation of the project to the manufacturing and test phase.

1.7 Project conclusion and perspective

The project has performed the first steps in the process of documenting the RFC demonstration unit for reducing methane emissions from natural gas fired gas engines at Danish CHP plants. The design and engineering phase is completed and the first steps of the manufacturing phase have been initiated.

The project is severely delayed. A detailed plan for manufacturing, shipping, installation and testing was prepared by SMC in the Year End Report. The plan is also published in the interim report submitted January 24, 2014. According to this plan installation at Dronninglund Fjernvarme should start August 2014 and testing phase should begin October 2014.

However this plan was never effectuated due to difficulties finding new capital and reconstructing the SMC company.

During the years of the projects running period the Danish natural gas fired gas engines at the CHP plants have continuously faced more and more unfavourable conditions regarding price of the produced electricity. The consequence is less and less operating hours.
Facing these realities Smart Muffler and the representatives for the new funding company were not too happy to experience the decrease in operational hours of Danish gas engines in CHP plants, but were continuously interested in completing the project and experience results from the test of the catalyst. At the latest telephone conference June 2015 SMC expressed little interest in pursuing a test run in Denmark given the poor future market prospects for the RFC technology in Denmark.

June 2015 the operator at Dronninglund Fjerne informs that the plant no longer are able to host the demonstration plant. By April 1 2015, the plant has switched to operate at the free electricity market and due to very low prices on electricity the gas engines are seldom in operation. During April, May and first half of June the engines have been in operation for a total of 3 hours.

During the recent five years the development on the Danish energy market have gradually reduced the relevance of the RFC technology and it is our opinion that the project cannot be completed within a reasonable time schedule and without exceeding the project economy by a considerably amount.

Taking all the above-mentioned circumstances into consideration Danish Gas Technology Centre recommend to terminate the project with no further activity.

Annex

Gannt Chart showing project overview