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HeatCore – An ultra-compact and fuel flexible catalytic boiler concept

(HeatCore – Ultrakompakt och bränsleflexibelt katalytiskt gaspannekoncept)

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"Catalyzing energygas development for sustainable solutions"

SGC Svenskt Gastekniskt Center AB

HEATCORE – AN ULTRA-COMPACT AND FUEL FLEXIBLE CATALYTIC BOILER CONCEPT (HEATCORE – ULTRAKOMPAKT OCH BRÄNSLEFLEXIBELT KATALYTISKT GASPANNEKONCEPT)

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Malmö 2013

Martin Ragnar
Verkställande direktör

Swedish Gas Technology Centre, SGC

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Malmö, Sweden 2013

Martin Ragnar
Chief Executive Officer

Authors' foreword

This project was initiated June 2012 and was finalized by the turning of 2012.

The following persons where active in the steering group, tied to the project.
Anna-Karin Jannasch, SGC
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Henrik Söderberg, PeakEco Energi AB

Catator is a catalyst- and system supplier and acts in a number of fields like emission technology, combustion technology and small-scale production of hydrogen for fuel-cell systems.

Dometic Group is a world-leading provider of leisure products for the caravan, motor home, automotive, truck and marine markets. The products are sold in almost 100 countries and are produced mainly in wholly owned production facilities around the world.

Smidmekgruppen is focused on large-scale production of machined components and acts as a sub-supplier to many companies. Their special interest in this project is to provide pressing tools for channel plates.

PeakEco Energy is an environmentally oriented company with focus on production of local energy from local raw materials such as waste and recycled sources.

Summary

An innovative catalytic heat exchanger has been evaluated in this project, financed by Catator AB, Smidmekgruppen AB, Dometic holding AB, Peak Eco Energi AB and the Swedish Energy Agency through SGC AB. The catalytic heat exchanger is abbreviated HeatCore™, and has been designed within Catator, based on long-term efforts devoted to this field [eg.1-4]. The major achievements are associated with a thermo-mechanically durable and compact heat-exchanger design, which is integrated with a fuel flexible catalytic burner comprising Catators proprietary wire-mesh catalyst. The condensing boilers are rapidly replacing older systems with atmospheric burners for environmental reasons. The addressable market within Europe is around 7 million units per year. The global market is above 20 million units a year. Thermal efficiency and low emissions are taken for granted but there is a great interest for compact and light units showing a high degree of fuel flexibility. Future legislation will put on demands concerning hybridization with renewable energy sources. In this light it is important to reduce the size of the boiler itself. The gas quality (parameters affecting the combustion characteristics) is believed to vary more in the future and the existing burner technology shows sensitivity to such variations. The market price for a typical 20-kW condensing primary heat exchanger is between 70 and 120 €/u. Since the HeatCore rely on a simple, compact and highly integrated design, market penetration is possible under these conditions. A complete condensing boiler for domestic applications was designed, constructed and evaluated in the project. It was found that the geometric measures of the complete boiler could be decreased by almost 40% over leading brands in Europe. The thermal efficiency reached peak values (above 107% based on the LHV of natural gas) and the NO_x-emissions were below any available standards. The major issues associated with primary heat exchangers are attributed to corrosion phenomena and thermo-mechanic failures. Indeed, the structural design of the heat-exchanger plates and the method of assembling these plates on to each other are crucial ingredients to overcome any such problems. The HeatCore-unit is based on round plates to reduce any stress concentrations during transient heating/cooling. Also, the flow pattern is designed to guarantee efficient cooling of regions susceptible to high local temperatures due to extreme heat transfer capacity adjacent to the burner section. It was demonstrated that the maximum temperature of the metal structure could be kept below 100-120°C during operation. Strain-stress calculations indicate a critical maximum temperature of around 120°C for a projected lifetime corresponding to 15 years. A special method for accelerated thermo-mechanic testing was developed and the design was verified by150,000 full thermal cycles without failure. The extensive fuel flexibility of catalytic combustion was demonstrated in the HeatCore-unit by replacing natural gas with LPG, digestion gas, pyrolysis gas and town gas (low-BTU-gas) without any changes in the construction. The design flexibility and the scalability of the concept were verified by construction of a non-condensing boiler for leisure applications (5-10 kW_t, fuelled by LPG). The HeatCore-concept was also redesigned for industrial applications 100 – 400 kW_t and tentative design criteria and CAD-images are presented and discussed in the report. The intention is to perform a third-party evaluation of the HeatCore concept and to construct and evaluate an industrial unit in the next project phase.

Referatsammanfattning

I detta projekt, som finansierats av Catator AB, Smidmekgruppen AB, Dometic Holding AB, Peak Eko Energi AB samt SGC AB (Energimyndigheten), har en innovativ katalytisk värmeväxlare utvärderats. Den katalytiska värmeväxlaren, benämnd HeatCore™, baseras på ett långvarigt utvecklingsarbete inom Catator, som bedrivits under mer än 10 år [1-4]. HeatCore-enheterna avses ersätta brännare/primärvärmeväxlare i gaseldade kondensationspannor. De primära attribut som kan tillskrivas HeatCore-tekniken är tekniska topprestanda (verkningsgrad och emissionsnivåer) i en ultrakompakt och lätt konstruktion. Enheten baseras på en rund värmeväxlardesign med en centralt placerad luftkyld katalytisk brännare applicerad ovanpå värmeväxlarkroppen. Genom att variera antalet plattor i värmeväxlarkroppen kan designeffekten påverkas inom ett relativt stort intervall.

Affärsmässigt gäller att pannmarknaden domineras av ett fåtal aktörer, ca 10-talet i Europa samt en handfull i Japan/Sydkorea respektive i USA. Systemtillverkarna fungerar i allt större utsträckning likvärdigt med biltillverkare, d.v.s. de köper komponenter från olika underleverantörer och står för design och montage. Då det gäller primärvärmeväxlaren så finns i dagens läge endast några få leverantörer och de har en närmast monopolistisk ställning. Det pågår (sedan ett antal år) ett paradigmskifte från atmosfäriska brännare/icke-kondenserande pannor till premix-brännare/kondenserande pannor med högre verkningsgrad. De kondenserande pannorna baseras i allmänhet på spiraliserade rörkonstruktioner av rostfritt stål eller av gjutna aluminiumkonstruktioner. Dessa enheter kombineras sedan i allmänhet med utrustning för flamförbränning. Typiska geometriska prestanda uppgår till 0.7 – 1 liter/kW respektive 0.5 - 1 kg/kW för brännare och värmeväxlare. Verkningsgradsmässigt ligger man i allmänhet nära den teoretiska gränsen samtidigt som emissionerna oftast uppfyller de strängaste miljönormerna. Systemtillverkarna värdesätter ökad konkurrens inom området samtidigt som de vill begränsa systemvolym och vikt. En kompakt och lätt konstruktion ökar möjligheterna till hybridisering med annan miljöteknik (t.ex. värmepumpsteknik etc). Okänslighet för variationer i bränslekvalitet är en annan aspekt som värdesätts av panntillverkarna. HeatCore-enheten har en effektdensitet motsvarande 10 kW/liter (0.1 liter/kW) respektive 10 kW/kg (0.1 kg/liter). Sett i detta perspektiv möjliggör således HeatCore-tekniken väsentliga volym- och materialbesparingar. Eftersom de heta ytorna i pannutrymmet kan reduceras kan de s.k. passiva förlusterna i pannan också reduceras, vilket leder till viss energibesparing (någon procent på årsbasis). Under drift uppnår HeatCore-modulerna en likvärdig verkningsgrad som de bästa alternativen på marknaden. Genom användning av katalytisk förbränning kan man i princip uppnå nollemissioner avseende kväveoxider, vilket inte är möjligt med konventionell förbränning. Prisbilden avseende brännare/primärvärmeväxlare är ytterst pressad med typiska nivåer på 70 – 120 €/enhet (18-25 kW), något beroende av volymer. Beroende på stor materialbesparing, rationell produktion och hög grad av integration bedöms HeatCore-modulerna ha en kostnadsnivå som möjliggör effektiv marknadspenetration. Det primära marknadssegmentet är fastighetsuppvärmning (ca 25 kW_t) där den adresserbara marknaden i Europa uppgår till ca 7 miljoner enheter per år. I ett globalt perspektiv försäljs över 20 miljoner

enheter per år och marknaden växer stadigt. Beroende på HeatCore-enhetens flexibla design återfinns kompletterande marknader inom fritidssektorn samt inom området industriell uppvärmning. Dessa marknader är väsentligt mindre men kännetecknas av andra krav på prestanda och förväntad livslängd/servicebehov.

Inom detta projekt har en HeatCore-modul implementerats i en komplett pannmodul med fullständig styr-och reglerutrustning samt utvärderats. Jämfört med existerande pannor på marknaden visade det sig möjligt att minska pannvolymen med 30 – 40% redan i den första designiterationen. Pannmodulen utgör en kombinerad enhet för uppvärmning och varmvattenproduktion i effektklassen 20 kW. Själva HeatCore-modulen har en geometrisk volym av ca 2.5 liter samt en vikt av 2.5 kg. Enheten förses med en gas/luft-blandning genom ett fläkt/ventil-system (likatrycksregulator). På vattensidan arbetar enheten mot en trycksatt primärkrets där vattnet cirkuleras med en vattenpump med låg effektförbrukning (ca 10 W_e). Tryckfallet genom HeatCore-modulen är lågt och möjliggör således besparingar i eleffekt (pump-och fläktarbete) jämfört med de flesta alternativ på marknaden. På vätskesidan kan tryckfallet begränsas till ca 100 mbar medan motsvarande tryckfall på gassidan ligger under 1 mbar. Huvuddelen av tryckfallsförlusterna uppstår i ventiler och armatur. Verkningsgraden har uppmätts till över 107% (beräknat på det effektiva värmevärdet hos naturgas) vid vattentemperaturerna 30/50°C samt ca 98% vid 60/80°C (bristfällig kondensation). NO_x-emissionerna ligger kring 15 ppm (0% O_2), något beroende av lastnivå och luftöverskott. Anläggningen är okänslig för variationer i luftöverskott (lambdavärde) samt för variationer i bränslekvalitet. Lågvärdesgaser (rå biogas samt pyrolysgas och stadsgas) har testats med bra resultat. På motsvarande sätt har gasol undersökts, speciellt med inriktning på fritidssektorn. CO-nivåerna är i nuvarande utförande något för höga vid full last och åtgärder pågår för att åtgärda dessa problem, som primärt hänför sig till underkylning av förbränningszonen.

I nuvarande panndesign är HeatCore-enheten och sekundärvärmeväxlaren separata enheter men det är möjligt att fullt ut sammankoppla dessa enheter i ett senare skede för att ytterligare öka integration, minska antal detaljer samt behovet av rördragning i systemet.

Den tekniska riskportföljen omfattar potentiella problem med korrosion samt termomekanisk utmattning. Kondensatet från förbränningen har generellt ett pH-värde på 2 - 5 (kan t.o.m. bli så lågt som 1.5) och förorsakar korrosionsangrepp på många konstruktionsmaterial. Det är därför inte möjligt att utnyttja konventionell lödningsteknik (koppar-och nickellod) för att sammanfoga plattorna. HeatCore-enheterna bygger på sammanfogning genom svetsning av legerat stål, varigenom hela strukturen blir homogen med avseende på materialkvalitet.

För att undvika termomekaniskt inducerad utmattning är det viktigt att begränsa den maximala godstemperaturen till högst ca 120°C. Högst temperatur uppträder längs den centrala sammanfogningsflänsen i förbränningsutrymmet. Beroende på utförandet av denna kan övertemperaturen begränsas till några tiotals grader över kylmediumets temperatur (vatten). Nivån på övertemperaturen har kartlagts för olika utföranden och jämförts med teoretiska CFD-beräkningar och en god korrelation har uppnåtts. Termografimätningar har utförts på enstaka plattpar i en speciell rigg under drift för att bedöma och kartlägga gradienter och transienta fenomen. FEA-beräkningar (FEA=finita element beräkningar) har gjorts och dessa visar att den maximala temperaturen bör begränsas till ca 120°C för en predikterad livslängd motsvarande ca 2 miljoner termiska cykler. Vid 150°C begränsas den förväntade livslängden till några hundra tusen cykler, vilket dock är fullt tillräckligt inom t.ex. fritidssektorn. En rigg för accelererade utmattningsförsök har konstruerats varvid plattpar utsatts för 150,000 termiska cykler (upp till 120°C) utan några tecken på sprickbildning. Liknande försök vid väsentligt högre temperaturer (ca 200°C) ledde efterhand till sprickbildning och läckage. Resultaten verifierar således de teoretiska predikteringarna.

Inom fritissektorn är kraven på livslängd och prestanda helt annorlunda än inom fastighetssektorn. Livslängder på 5,000 timmar och några tiotusentals termiska cykler är fullt realistiska krav. Dessutom saknas tydliga emissionskrav avseende kväveoxider och CO. Kraven är mer inriktade på lukt och rök vid start och kontinuerlig drift. Man vill i allmänhet undvika kondensation varigenom HeatCore-enheten kan förenklas (göras ännu kompaktare). Effektnivån ligger i allmänhet på någon/några kW upp till ca 10 kW. Då det gäller bränslevalet är man inom detta segment primärt intresserade av gasol och flytande bränslen såsom etanol och diesel. HeatCore-enheten kan kompletteras med ett brännarhuvud som möjliggör förbränning med såväl gasformiga som vätskeformiga bränslen. En icke-kondenserande HeatCore-modul för gasol har designats, konstruerats och utvärderats inom ramen för projektet.

Panntillverkare som fokuserar på industriell uppvärmning efterfrågar enheter på minst 100 kW, primärt för naturgas. Tanken är att kunna kaskadkoppla flera sådana enheter för att bygga pannenheter med ännu större effekter (och utökad modulerbarhet). Inom projektet har designunderlag framtagits även för industriella pannor.

Sammanfattningsvis har projektet resulterat i en rad väsentliga slutsatser:

- HeatCore-enheterna kan implementeras i en panna, varvid signifikanta volyms-och viktbesparingar är möjliga (ca 40% volymreduktion)
- Tekniska prestanda har verifierats (emissioner, verkningsgrad, respons)
- Riskerna för termomekanisk utmattning har utretts och designkriterier för att undvika dessa fenomen har fastlagts teoretiskt och experimentellt
- Skalbarheten hos konceptet har utretts och demonstrerats
- Olika lågvärdesgaser samt gasol har testats i HeatCore-enheten med gott resultat

Det avslutade projektet utgör den första etappen i en mer omfattande utvärdering/verifikation av HeatCore-konceptet. I nästa fas kommer en tredje part att utföra kompletterande utredningar av konceptet samt genomföra ett långtidstest för att uppmäta/verifiera parametrar såsom årsverkningsgrad, hållbarhet etc. Avsikten är också att konstruera en industriell HeatCore-modul i storleksordningen 200 kW och utvärdera denna i samarbete med lämplig panntillverkare.

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1.Background

Catalytic combustion has been known for a long time. Indeed, the phenomenon is mentioned already during the 19th century by researchers like Davy and Mischerlich [5]. However, it took a very long time before catalytic combustion became a relevant field in catalytic science and the technology development was spurred by increased environmental demands concerning emissions of nitrogen oxides during the 80s and 90s.

A number of studies were directed to suitable combustion catalysts for methane (the main component in natural gas) [eg. 6-8]. Relevant characteristics were associated with high activity, low ignition temperature and a high durability in the combustion environment. It relatively soon stood clear that Palladium possessed specific merits in the combustion of methane. By including traces of other elements into the Palladium phase it was possible to further increase the activity [9].

Since catalytic combustion is a high-temperature process, it was found that problems with catalyst deactivation were lurking in the background and reducing the practical use of catalytic combustion. Consequently, it was necessary to stabilize the active phase on a suitable carrier material, which could tolerate extremely high temperatures without sintering. Some interesting formulations were found with stabilized alumina and hexa aluminates [e.g. 10-11].

Catalytic combustion of methane is possible at temperature above approximately 400°C, but the turnover frequency is relatively low at these temperatures. If sulphur is present (odorant used in natural gas) the conversion graph is shifted to higher temperatures. Combustion of sulphur containing natural gas is not possible below 550 – 600°C due to formation of Palladium sulphate [12].

To gain any practical use of catalytic combustion, the combustion temperature should stay above 900°C. At these temperatures the turnover frequency is relatively high and the amount of catalyst can be reduced to realistic levels. At temperatures between 900 and 1,000°C it is also possible to handle material problems (thermal corrosion), catalyst deactivation (sintering and evaporation) and to counteract possible poisoning phenomena caused by sulphur.

The traditional catalytic reactor will normally contain a pellet catalyst, a monolith or a sintered catalyst body. Such systems are extremely sensitive to internal overheating caused by transient operation and variations in lambda value and/or gas quality. Indeed, the lack of a suitable geometric matrix effectively hindered commercial breakthrough of catalytic combustion for a long time. Research performed in collaboration between Chemical Engineering at Lund University and Catator in the early 90s resulted in a new type of geometric matrix for catalytic combustion, i.e. the wire-mesh catalyst [13-14]. By applying single wire-meshes in the combustion environment it was found possible to circumvent the destructive problems with catalyst overheating. Single wire meshes are effectively protected against overheating by radiant cooling.

With single wire-mesh catalysts, it was also possible to reduce the lambda value in combustion to gain thermal efficiency in the overall process (reduced flue gas losses). Increasing the load and reducing the lambda value resulted in a new type of combustion process, usually called hybrid combustion or catalytically assisted homogeneous combustion [15]. Figure 1 below indicates various modes of combustion on a wire-mesh catalyst. At extremely low loads, the combustion is entirely in the catalytic mode and we shall see negligible emissions of nitrogen oxides. When the load is increased a relatively larger portion of the fuel is combusted downstream the catalyst in a region with high concentrations of free radicals, which are produced on the catalyst. At still higher loads we see a transition from this hybrid combustion to complete homogeneous combustion (blue-flame combustion) and the catalyst will cool down and become inactive. For economical reasons, most catalytic burners are designed for hybrid combustion. In this mode we obtain reasonable emissions also at high loads (small amount of combustion catalyst).

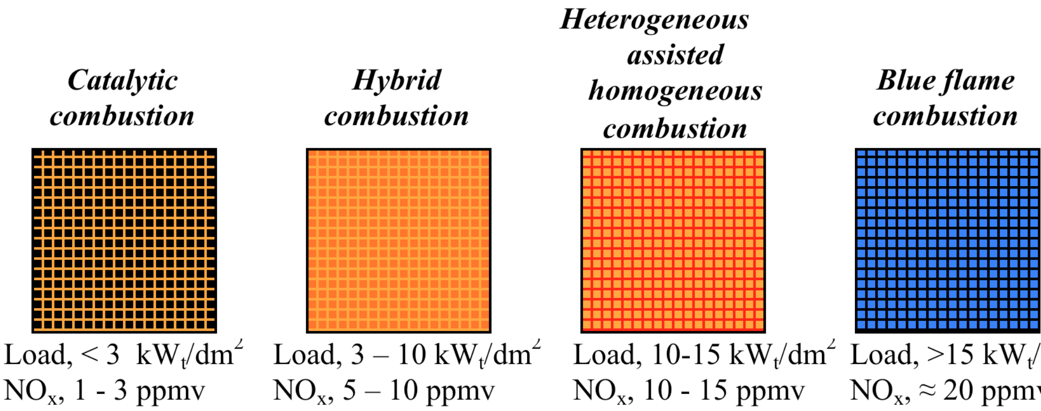

Figure 1 *Modes of combustion on wire-mesh catalysts [15].*
Catalytic combustion – only the glowing catalyst structure can be seen
Hybrid combustion – a plasma like appearance in the structure
Heterogenous assisted homogeneous combustion – transition phase
Blue flame combustion – the wire mesh acts as a flame stabilizer

Originally, the primary interest for catalytic combustion was associated with combustion chambers for small-scale gas turbines [e.g. 16 – 17]. Catator, however, focused on the development of catalytic heat exchangers for boiler applications. Already from the beginning, it was clear that the wire-mesh concept could be combined with a plate-type heat exchanger. A number of studies were performed in collaboration with Värmeforsk and SGC [1-3, 18]. These studies resulted in a massive build-up of experience and knowledge in the field. A comprehensive development programme was initiated together with SWEP International by the turning of the 90s with the goal to forward a complete catalytic heat exchanger based on their proprietary heat-exchanger technology. An extremely compact and integrated device was constructed and evaluated with encouraging results [19]. Problems with corrosion and thermo-mechanic failures in the heat-exchanger body, however, prevented further development.

By constructing the catalytic heat exchanger in a similar manner as a plate-type heat exchanger it is possible to enable an extreme scalability of the concept. Early contacts with boiler manufactures during the 90s indicated a firm focus on compactness, low weight, scalability and fuel flexibility. Emission footprints were important but secondary in relation to other parameters mentioned. By the turning of the 90s we also saw a paradigm shift from old installations with atmospheric burners and non-condensing boilers to pre-mixed combustion in condensing boilers. Indeed, thermal efficiency came on the agenda. Studies directed to thermal efficiency showed that the plate-type heat exchangers were able to reach peak performance with efficiencies close to the theoretical limit.

Catalytic combustion is quite different from flame combustion and is not sensitive to variations in gas qualities. Definitions such as flame lift and flashback are generally not applicable. Catalytic combustion is possible in wide regions of a standard Delbourg diagram (figure 2) whereas we foresee problems in flame combustion. LPG, various natural gas qualities, digestion gas, landfill gas, pyrolysis gas, town gas, reformate gas and tail gas (fuel cell applications) can all be burned in a catalytic burner. The green shaded area indicates regions were catalytic combustion normally works.

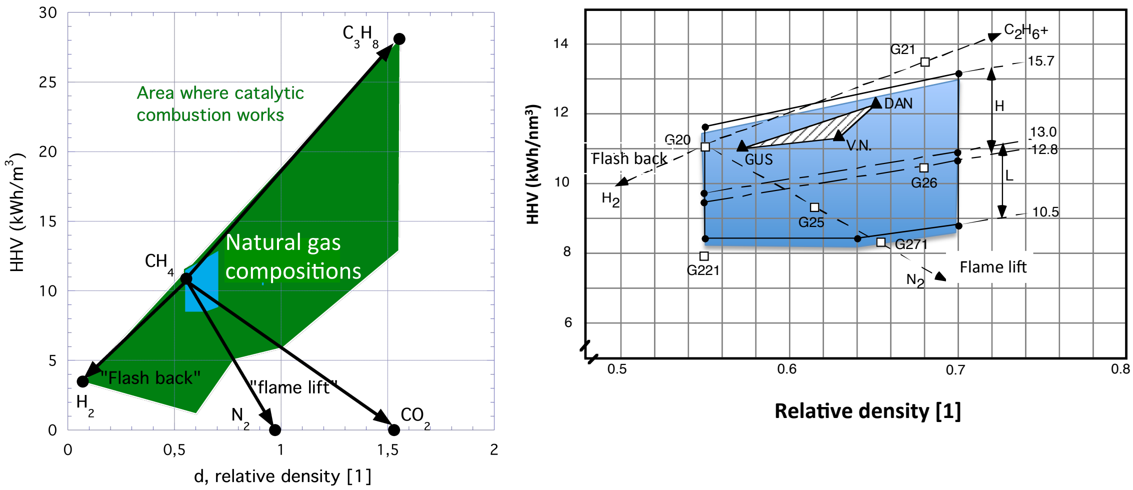

Figure 2 The fuel flexibility in catalytic combustion. Blue shaded area magnified in the right diagram. The natural-gas quality in Sweden is normally within the triangle (GUS-DAN-V.N.).

Fuel gases are normally divided into four categories according to [46, 47]:

- Town gas (1A)
- Natural gas (2H, 2L, 2E)
- LPG (3B/P, 3P, 3B)
- Mixtures between fuel gas and air

A number of reference gases are used to investigate the performances of various gas appliances, e.g.:

G20	100% CH_4
G21	87% CH_4, 13% C_3H_8
G221	69% CH_4, 16% N_2, 15%H_2
G222	77% CH_4, 23% H_2
G23	92.5% CH_4, 7.5% N_2
G24	68% CH_4, 12% C_3H_8, 20% H_2
G25	86% CH_4, 14% N_2
G26	80% CH_4, 13%N_2, 7% C_3H_8
G271	74% CH_4, 26% N_2

Limits for natural gas compositions with a relative density between 0.55 and 0.7 and Wobbe numbers between 10.5 and 15.7 are shown in the figure (blue shaded area). Catalytic combustion is thus possible for all gas families without replacing or redesigning the burner head. The blue shaded area is magnified and reference gases as well as typical gas qualities on the market are highlighted [46]. In Sweden we may see mixtures between gases from Russian (GUS) , Danish (DAN) and Norwegian fields (V.N.). The triangle (GUS – DAN – V.N.) shows possible characteristics with respect to the relative density and the higher heating value (HHV).

Approximately two years ago, it was decided within Catator, to develop a new type of combined catalytic burner/heat exchanger, abbreviated HeatCore™. The HeatCore-modules should be characterized by the following attributes:

- Compact design, 7 – 10 kW/litre
- Light weight, 7 – 10 kW/kg
- Homogenous material composition to avoid corrosion
- Design for production, low production cost
- Turndown in excess of 1:10
- Wide fuel flexibility
- High thermal efficiency; 100 – 109% (related to LHV) depending on water temperatures
- High degree of integration
- Scalable design, a few kW - >100 kW, plate size and number of plates might be varied
- Low emissions – should reach all available standards, zero-NO_x is possible but not demanded in the market for the time being
- Durable design, which could tolerate at least 300,000 thermal cycles and continuous operation for 15 years

The geometric demands and most of the technical demands were reached from the beginning. The primary question marks were associated with robustness, durability and lifetime. Based on our background experience, thermo-mechanic fatigue is an important area to address theoretically and experimentally. Since the thermal flux is extremely high adjacent to the combustion chamber, the flange tips joining individual plates might get very hot. If the temperature exceeds a critical value cracks might be formed following a number of thermal cycles giving rise to water leakage.

Possible issues with corrosion can be reduced/eliminated by avoidance of sensitive brazing agents in the structure. Corrosion is, however, extremely complicated to predict from a theoretical viewpoint and long-term testing is mandatory. Some boiler manufactures have developed accelerated corrosion tests, which can reveal critical processes within approximately one year (instead of 15).

A number of relevant standards and norms are applicable to the HeatCore-unit. Such standards include efficiency, emissions, handling of condensate, installation, safety etc [20 – 28].

The objective of this project is to investigate the technical performances of the HeatCore-module in a complete boiler installation and to evaluate various gas qualities. Special measures are directed to the technical risk portfolio including thermo-mechanical failures. A follow-up project is suggested involving a long-term test performed by third party.

2. Objectives

The overarching goal with the project was to verify the function and performances of the HeatCore-module in a complete boiler system and to develop the understanding concerning thermo-mechanical fatigue.

To facilitate these studies a complete boiler installation was constructed including all necessary balance-of-plant components and a complete control- and safety system. One aim when constructing the boiler was to demonstrate the possibility to build it extremely compact in order to reduce the size of the boiler cabinet. Since it is possible to reduce the size and to increase the integration, the weight of the boiler will also be reduced. This will in turn make transportation and installation easier.

The HeatCore technology is characterized by a great flexibility with respect to the fuel qualities and the effect output. One aim was to demonstrate the operability with various fuels like NG (H/L), LPG, digestion gas, pyrolysis gas and town gas (i.e. reformate gas).

There exist various technical and geometrical demands in different market segments. Indeed, the most stringent demands concerning emissions, efficiency and robustness are found in the domestic sector. In the leisure area, the demands concerning emissions, efficiency and lifetime are less pronounced. Consequently, these boilers are typically non-condensing and often show higher emission footprints. A non-condensing HeatCore-module for LPG rated at 10 kW was designed, constructed and evaluated as a part of the project.

The HeatCore technology can also be expanded to industrial heating. Discussions with relevant manufactures of industrial boilers resulted in a specification of demands for such units. A tentative design for an industrial HeatCore-module is discussed in this report.

Finally, relevant objectives for a follow-up project are discussed. Such a project shall focus on third-party evaluations and long-term testing. As an additional ingredient, it is also proposed to construct an industrial HeatCore-module with a rated heat output of approximately 200 kW.

3. The Heat Core^{TM} concept

Previous work in the field of catalytic heat exchangers has demonstrated problems with corrosion and thermo-mechanical issues due to high temperature gradients and the aggressive chemical environment. The HeatCore-concept was originally developed within Catator and the idea was to combine a catalytic burner head with a round heat-exchanger body comprising a homogenous material composition (all-welded structure). The catalytic burner is placed outside the heat exchanger and no separate cooling is required for this detail. This also means that it is easy to get access to the combustion catalyst and to assemble/disassemble the unit.

The flue gases are collected in a plastic cover and the condensate is separated from the flue gases and rejected to the sink. The overall volume of the HeatCore-unit is between 2.5 and 3 litre depending on the heat output (20 – 25 kW).

The heat exchanger is around 170 mm in diameter and the plate thickness is around 0.5 mm. The plates are pressed according to a proprietary pattern to guarantee one-step condensation, low pressure drops and effective and uniform temperature control of the plates. The plate pattern has been evaluated by CFD-modelling. As shown in Figure 4, the gas temperature levels off extremely quickly when passing over the cooled plate. Following a few mm, the temperature of the gas has reduced from about 1400-1500°C down to a few hundred centigrade. The temperature at the outlet will be very close to the cooled plate (in this case about 10°C higher). In this simulation the inlet water temperature was assumed to be 30°C and the outlet water ca. 50°C, i.e. a normal condition of operation.

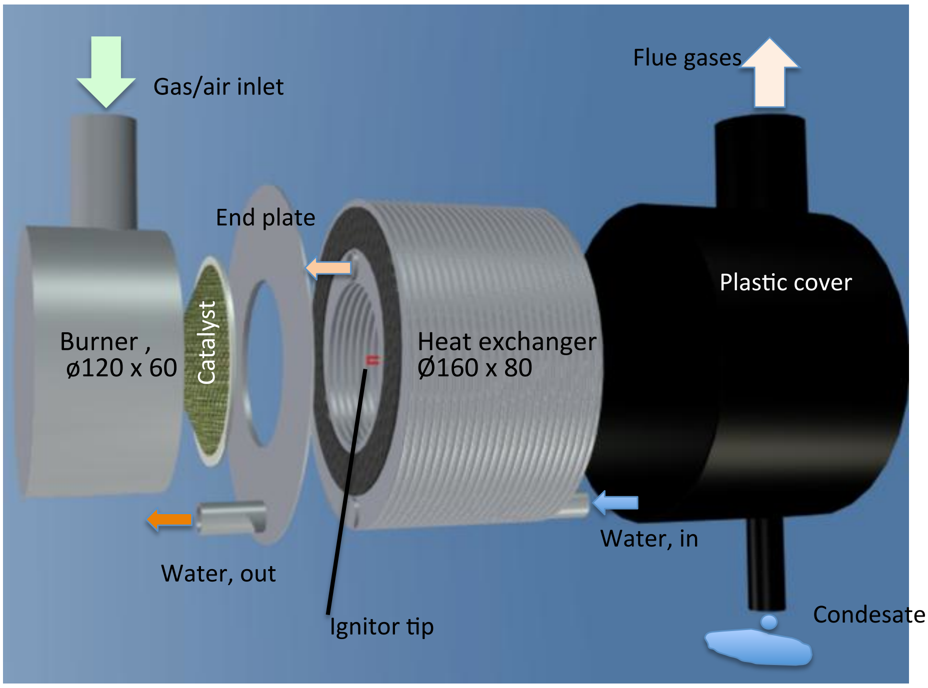

Figure 3 Elements of the HeatCore module

The pressure drop on the water side can be further decreased by increasing the pressing depth of the plate on this side. The water-side pressure drop affects the electric power consumption and should be as low as possible without giving rise to poor distribution.

The heat transfer capacity on the gas side increases when the distance between individual plates is reduced. By reducing this distance it is possible to reduce the number of channel plates needed for a specific heat output. However, it is also important to enable effective removal of condensate water, which otherwise might collect between plates and give rise to increased pressure drop and poor gas distribution.

In non-condensing boilers the heat-transfer area might be reduced (less plate diameter) to give an even more compact structure.

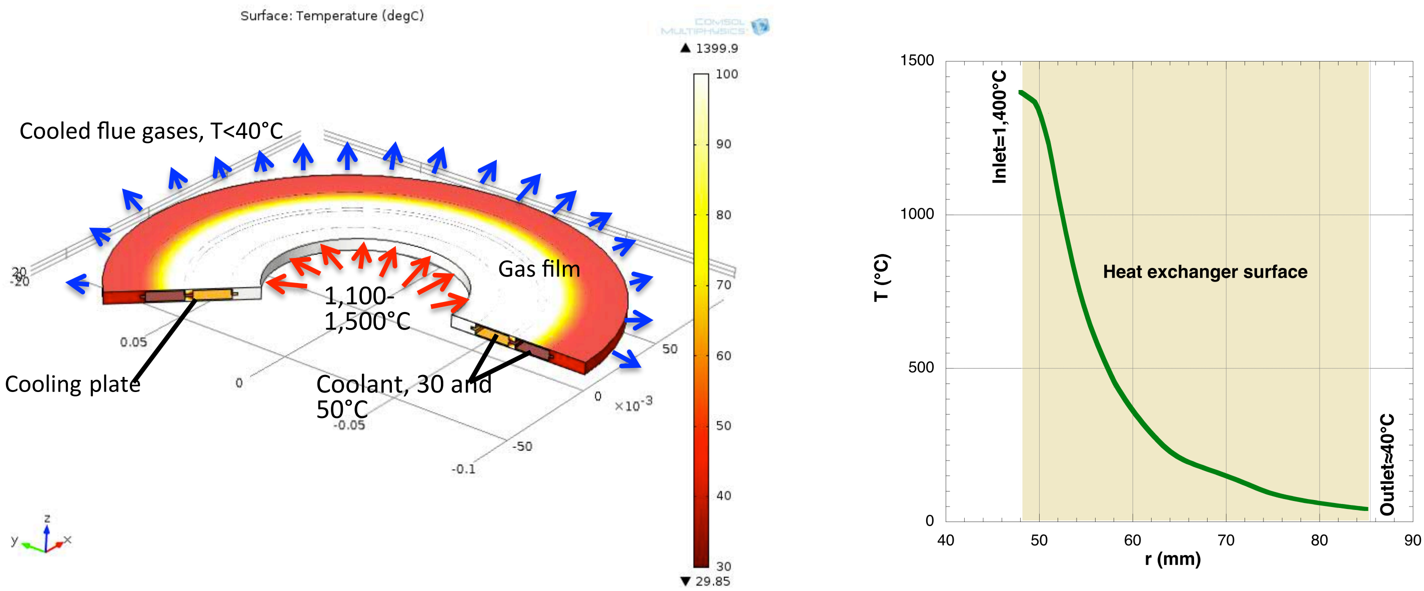

Figure 4 Temperature gradient on the gas side. Gas inlet temperature 1,400°C at rated load (25 kW) and air-excess ratio=1.35.

As an alternative to steel plates, it is also possible to use plates produced from aluminium. The thermal calculations indicate less thermal gradients in such plates due to the much higher thermal conductivity of this material.

Premixed gas and air enters the air-cooled burner head and is led through the combustion catalyst, which consists of a conic formed wire-mesh substrate. The combustion process is in the hybrid mode, which means that free radicals are formed and released to the boundary layer found downstream the catalyst. These radicals function as a homogenous catalyst for the combustion process. Even if some flames may form at high loads, the combustion zone is shrunk by the presence of these free radicals. This also means that flame impingement and extremely high CO-levels can be avoided even in cases with extremely short residence times in the combustion zone. The use of short combustion times also reduces the formation of NO_x.

It is possible to increase the amount of combustion catalyst for even lower NO_x-footprints (zero emission), but such measures are not supported by the boiler manufactures since the cost then would increase. The performance of the combustion catalyst has been demonstrated for more than 10,000 hrs in third-party tests performed at Gaz de France – Suez [29]. No degradation was found in these tests even if the catalyst temperature continuously was kept at 900 – 1,000°C. The combustion catalyst is based on a backbone of FeCrAlloy (e.g. Kanthal AF), which is catalysed according to Catator s proprietary catalyst technology [49]. The lifetime of the wire itself is above 100,000 hrs at temperatures around 900°C, according to information obtained from the supplier.

Since the combustion process partly is in the catalytic mode, the ionization current is much lower than in normal flame combustion. The ionization current must thus be reinforced for a safe detection of the combustion process. Ignition can be performed by a standard spark plug or a glow plug.

4. Market survey and product pricing

As previously mentioned, the global domestic boiler market is huge and more than 20 million boilers are installed each year. The market structure is typically oligopoly with only a few players dominating each market. In Europe, there are perhaps 10 significant players who stand for the majority of the 7 million units sold per year. The pie diagram in Figure 5 shows an approximate breakdown of the market share of each predominant player in the European market a few years ago. As can be seen in the figure, Vaillant, Bosch and Baxi stand for almost 50% of the market. The market is relatively volatile with a lot of company fusions and reorganisations.

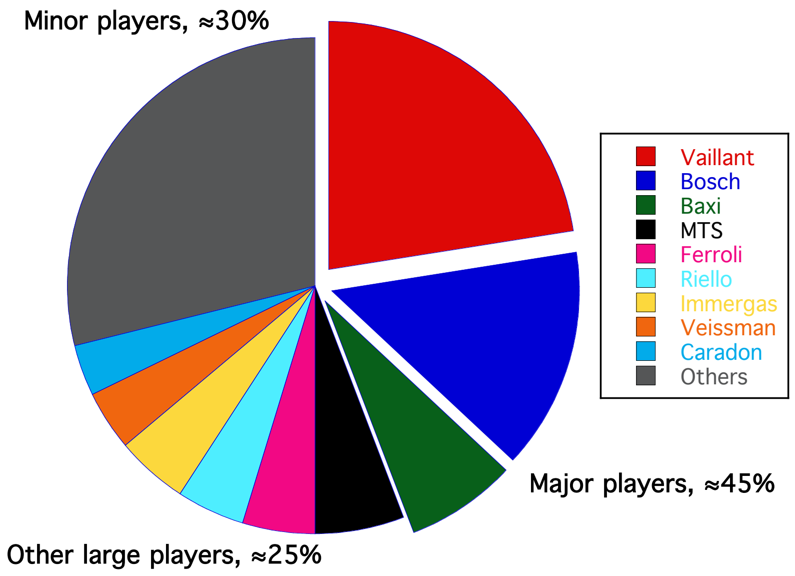

Figure 5 Breakdown of the European market
Total number of units sold: ca 7 million per year.

The competition among the manufacturers is harsh and the gross margin in sales is generally relatively limited. There is a big focus on measures to cut the production cost by increasing the integration or reducing size/weight and number of details in the systems. Technical performances with respect to thermal efficiency and emission footprint are normally well reached in relation to prevailing standards. There are new directives (ECO-directives) underway, which probably will strengthen some of the technical demands further [30]. Such demands will likely favour hybridized system, where the relative amount of renewable energy used in the system can be increased, e.g. combination between heat pumps, combined heat-and power and gas boilers

In discussions with boiler manufacturers it is evident that they are following a road map with the following ingredients:

- Cut production cost by material savings, process intensification and better integration
- Develop hybrid systems where the relative amount of renewable energy can be increased
- Focus on lifetime, robustness and reliability
- Reduce the electricity consumption by decreased pressure drops

The thermal efficiency is very close to the theoretical limit and the emission footprint is very low already. According to a mapping performed by the Danish Gas Technology Centre, a typical gas boiler installed in Scandinavia will show an average efficiency on a yearly basis of around 100% (Calculated on the LHV of natural gas) whereas the total NO_x-emission is limited to 0.2 – 1 kg/year [31].

There exists a possibility to increase the average efficiency somewhat (1-3%) by reducing the passive losses from hot surfaces in the boiler. The NO_x-emissions can also be reduced by a few ppm. However, there exists a firm trade-off between the relevance of these minor improvements and the increased cost.

The HeatCore-module will replace the primary heat exchanger and the burner in the boilers. Such units are normally bought from external suppliers even if some boiler companies also have in-house production of such devices. The predominant supplier of primary heat exchangers in Europe is Giannoni [32]. Their technology is based on a winded steel tube, which contains the combustion chamber. A slotted tubular flame combustor is installed in the central combustion chamber. This solution typically reaches effect densities in the region of 1.5 kW/litre and 2 kW/kg. The thermal efficiency is high and the emissions are low. Some boiler manufacturers have focused on casted aluminium structures, but problems with corrosion have been discussed. To overcome such problems it is conventional to overdesign the material thickness. At the moment Giannoni probably stands for more than 50% of the European market for primary heat exchangers.

A lot of research and development is devoted to find more compact and integrated design solutions but different technical and economical barriers have until now prevented any commercial success. The accepted cost for a primary heat exchanger including burner is currently in the window 70 – 120 € depending on purchased volumes and possible tailoring of the product. Indeed, it is important to find cheap materials of construction, to decrease the material consumption and to find a rational method for production.

The HeatCore-module reaches a effect density of around 10 kW/litre and 10 kW/kg respectively. In addition the unit is designed for easy manufacturing and assembly and the burner part can be greatly simplified in relation to the conventional slotted burner heads. Production cost calculations show that the HeatCore module can be produced and sold at the prevailing market price with an acceptable margin. Simultaneously, the units will provide added values with respect to compactness and a higher degree of integration. The boiler cabinet can be built relatively more compact than today, which will result in secondary savings, easier transportation and installation.

Also the leisure market has an oligopoly structure with a relatively limited number of players (e.g. Eberspecher, Webasto, Alde, Truma and Dometic). Focus is on heating systems for mobile applications, like trucks, caravans and campus. LPG and liquid fuels like ethanol, kerosene and diesel are the predominant fuels. Critical factors are mainly associated with cost issues, reliability and simplicity. Demands concerning thermal efficiency and emission footprint are less stringent and the most important criteria are to avoid visible smoke, odour sensation and combustion sound. The total market size is less than 5% of the domestic boiler market but we are still talking about some hundred thousand sold units per year.

Many domestic boiler manufacturers also produce systems for industrial heating (100 kW+). Major demands are similar as for domestic boilers. Effect densities are even more important here since the size of the integrated primary heat exchanger/burner is relatively more pronounced in these systems. The HeatCore-module opens up for interesting design solutions also in this field.

Figure 6 below indicates how the HeatCore-module can be modified/tailored to fit into different applications on the market.

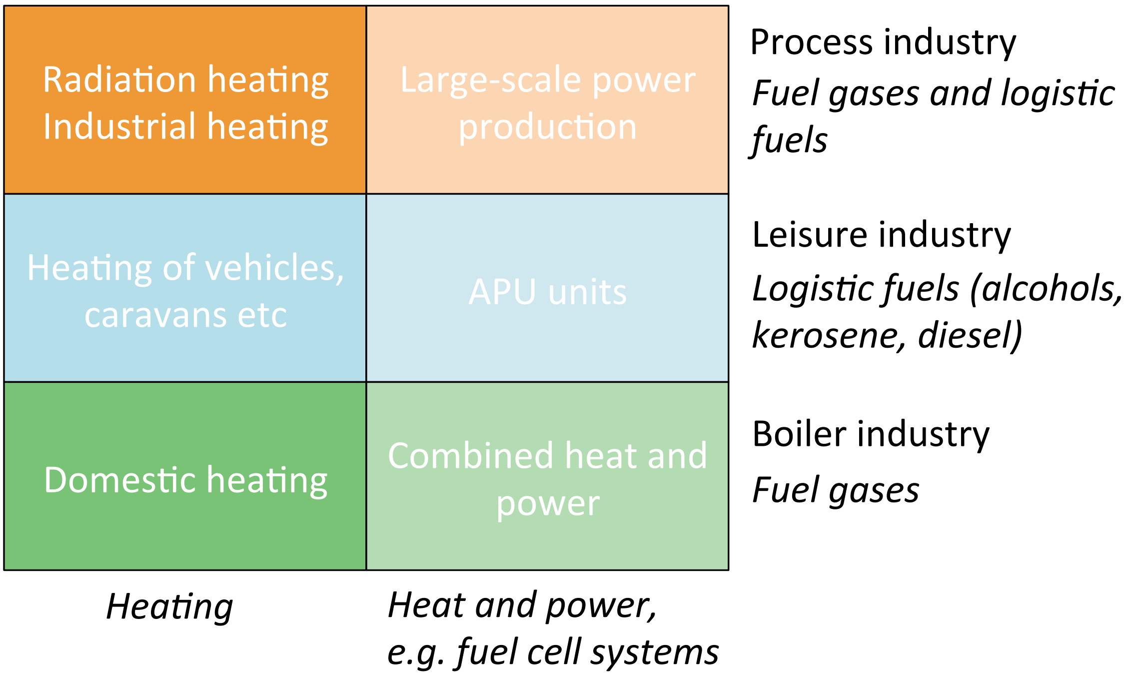

Figure 6 Market versatility of the HeatCore

The standard HeatCore-module with an integrated catalytic burner has been developed for domestic heating applications. It is also possible to use this unit in systems for combined heat- and power. In the leisure area the heat exchanger may be simplified since no condensation is demanded. In addition we are talking about smaller systems where the burner head should be replaced by a multi-fuel head enabling combustion of fuel gases as well as liquid fuels. Such units can also be used in future APU (power- and heat generation) for the mobile sector. In industrial heating, the natural choice of fuel is natural gas. The heat exchanger and the burner must be designed for capacities beyond 100 kW+. Such units might be installed as individual units or several in parallel (cascade).

As indicated in this section, the market perspective is indeed intriguing with a lot of opportunities and many possible business cases. Due to the oligopoly structure of the market it is also fairly simple to market the products business-to-business wise. These OEM-costumers will then address the end consumers.

5. Specification of demands

There are a number of demands and requirements on the HeatCore-module. In addition, a number of relevant standards and directives must be followed.

The HeatCore-module has the following physical **interfaces**:
- Connection to gas/air inlet (i.e. to fan/valve-package)
- Connection to flue gas outlet
- Water connections (in and out)
- Connection for condensate drain
- Ignitor and combustion detection (electrical connectors)

The HeatCore-module has a number of relevant **functions/characteristics**:
- Heat generation (safe and effective combustion) and heat transport
- Heat transfer from hot flue gases to water
- Enable flue gas condensation and condensate draining (condensing boilers)
- Guarantee tightness of the water circuit, i.e. no external or internal leakage
- Prevention of any gas leakage from the unit to the cabinet (fuel gas or flue gases)
- Provide resistance to chemical, thermal and mechanical influences during operation and idling/hibernation
- Show insensitivity to the maximum pressure in the water circuit

Two European **directives** are applicable [33-34]:
- Gas appliance directive (90/396/CEE)
- Efficiency directive (92/42/CEE)

An ECO-directive is pending and might show relevance in a near future.

Relevant European **standards** are [20-24]:
- EN 483
- EN 625
- EN 677
- EN 437
- EN 297

The development of the HeatCore-module has relied on the following specification of demands, which might be expanded with new demands underway:

1.Primary application

Heat output: 5 – 60 kW thermal (domestic field)

Excess air ratio: 1.2 – 1.4 (1.5)

Gas types: Natural gas type H/L, LPG, low-BTU gases

Liquid fuels: ethanol, kerosene and diesel (leisure sector)

2. Geometric features

Pressure loss, water circuit:	< 20 kPa @ 1.0 nm^3/hr
Pressure loss, fuel circuit:	<0.3 kPa @ maximum effect
Maximum water pressure:	6 bar(g)
Effect density:	>7 kW/litre, >5 kW/kg
Connections:	Fuel/air: top or front Flue gases: top or rear Condensate: bottom Water circuit: rear/front

3. Thermal performances (condensing boilers)

Efficiency at 30/50°C:	108% (related to LHV)
Efficiency at 60/80°C:	98% (related to LHV)
Maximum acceptable water temperature:	120°C
Maximum acceptable flue gas temperature:	130°C (higher with metallic cover)

4. Chemical resistance

pH-values:	1.5 – 5
dust/soot etc:	liquid fuels (leisure sector)
nitrates, sulphur, halogens:	may occur in various amounts in the conden-sate and in the water
water additives:	Corrosion inhibitors and glycol might be add-ed to the primary circuit

5.Noise

Combustion sound:	No resonance phenomenon should occur
Boiling water:	Boiling must not appear under normal operation

6.Life time and durability

Number of thermal cycles	300,000 (30,000 leisure sector)
Required lifetime	15 years (10,000 hrs leisure sector)

Indeed, the specification of demands is extremely challenging with respect to robustness, reliability and lifetime. It is important to verify the lifetime by accelerated lifetime tests in collaboration with a relevant partner. Especially the chemical environment is difficult to specify since the trace components found in the combustion environment may vary highly with geographic location of the installation.

6. Boiler installation

A HeatCore-module (20 kW) was implemented into a complete boiler system, designed end constructed by Catator. The boiler system comprises the following components:

- HeatCore module including the catalytic burner, the ignitor and the combustion detector (Catator)
- Air fan (EBM)
- Gas valve and gas injection system (Honeywell)
- Water pump (Grundfoss)
- Expansion vessel and safety valve
- Secondary heat exchanger for tap water (SWEP)
- Solenoid valve in primary water circuit
- Condensate drainage system
- Full control and automation (Catator)
- Safety system (Catator
- Boiler cabinet

A flow sheet diagram of the boiler installation is shown in Figure 7 below. The unit is built around a primary water circuit operating at around 3 bar(a). The pump is circulating the water in the primary circuit (usually connected to radiators or the floor heating system). In this system we use a plate-heat exchanger to mimic the heating system. The inlet temperature to the HeatCore-unit is normally around 30°C with an outlet temperature of around 50°C (set-point).

When hot tap water is required a pressure sensor will trig a change in the set point of the HeatCore-module. The outlet temperature is then normally increased to 60°C but this level can be adjusted according to the need.

The control system is equipped with an automatic start-up and shut down cycle involving relevant venting.

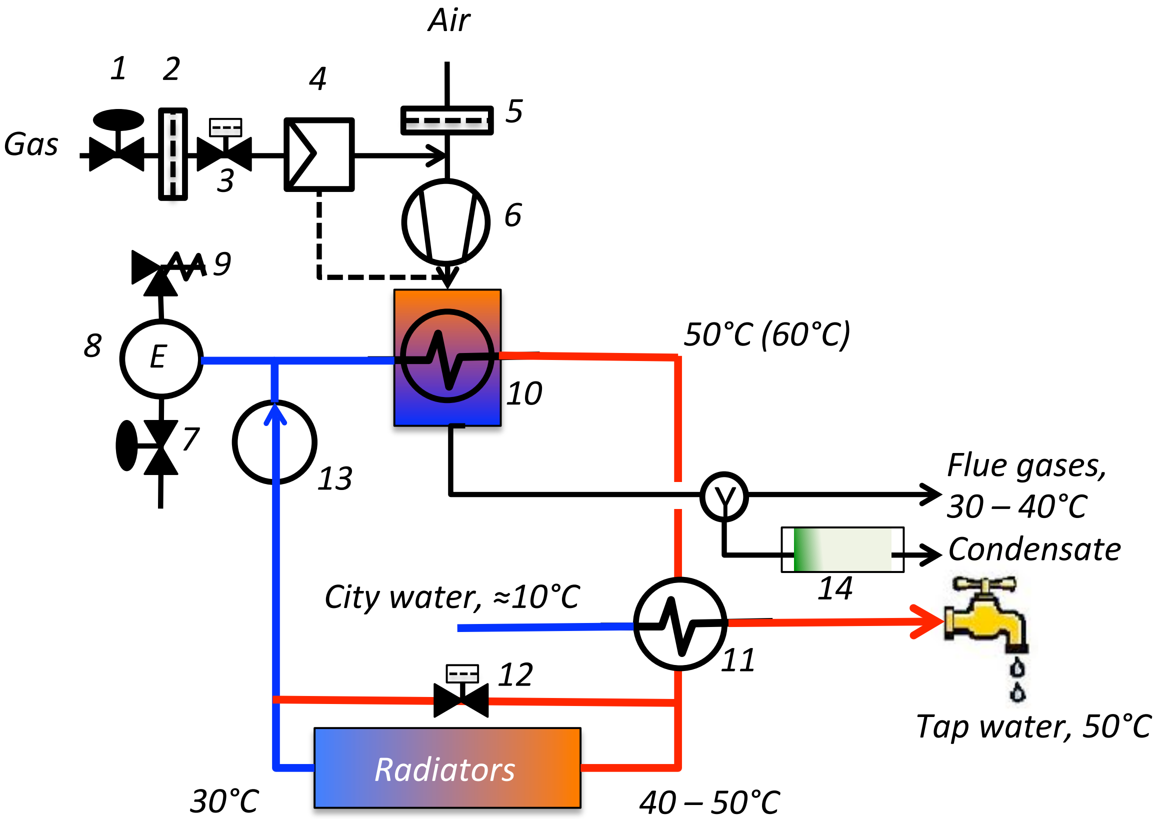

Figure 7 *Flow sheet of the boiler installation*
1=Manual valve, 2=Gas filter, 3=Shut-off valve, 4=Gas:air-regulator, 5=Air filter, 6=Combustion fan, 7=Filling-up valve, 8=Expansion vessel, 9=Safety valve, 10=HeatCore-module, 11=Secondary heat ex., 12=Solenoid valve, 13=Circulation pump, 14=Condensate filter

All components where assembled in a compact cabinet, as shown by the photo in Figure 8 below. The lower part of the photo shows the heat exchanger used to mimic the radiator (or floor-heating) system. The total volume of the unit is 60 litres with the overall dimensions of 520 x 400 x 280 mm.

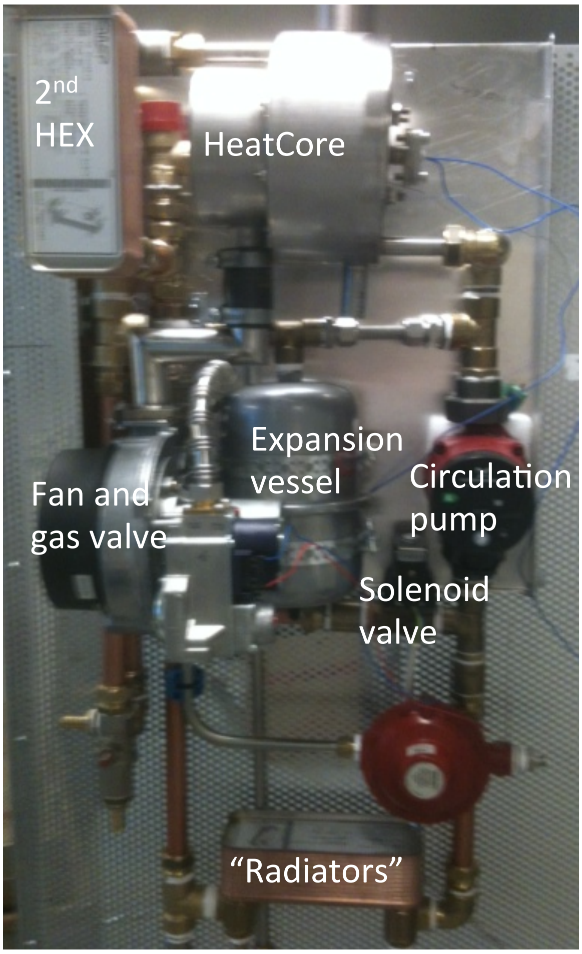

Figure 8 Photo of boiler installation

In Table 1, the size of the boiler cabinet is compared with similar units found on the open market, supplied by leading boiler manufacturers [35-39]

Table 1 Comparison of boiler sizes (20 – 25 kW-class)

Brand	Volume (l)	Height (mm)	Width (mm)	Depth (mm)	Weight (kg)
Catator, design iteration 1	58	520	400	280	<20
Catator, design iteration 2	44	480	350	260	<18
Vaillant-eco TEC plus	106	720	440	335	39
Bosch Greenstar 24i Junior	94	710	400	330	27
Baxi Neta-tec 24 GA	79	700	390	290	34
Ferroli Modena HD	77	600	400	320	29
Veissman Vitodens 330-W	155	850	480	380	48

The table clearly shows the possibility to save volume by replacing large primary heat exchangers with the highly integrated HeatCore-module. Further integration and refinement of the design let us believe that it were possible to reduce the volume by another 20 – 30% based on the components used in this prototype.

Integration of the HeatCore-module with the secondary heat exchanger indicates additional volume savings of around 25%. A tentative packaging of such a system is shown in Figure 9 below.

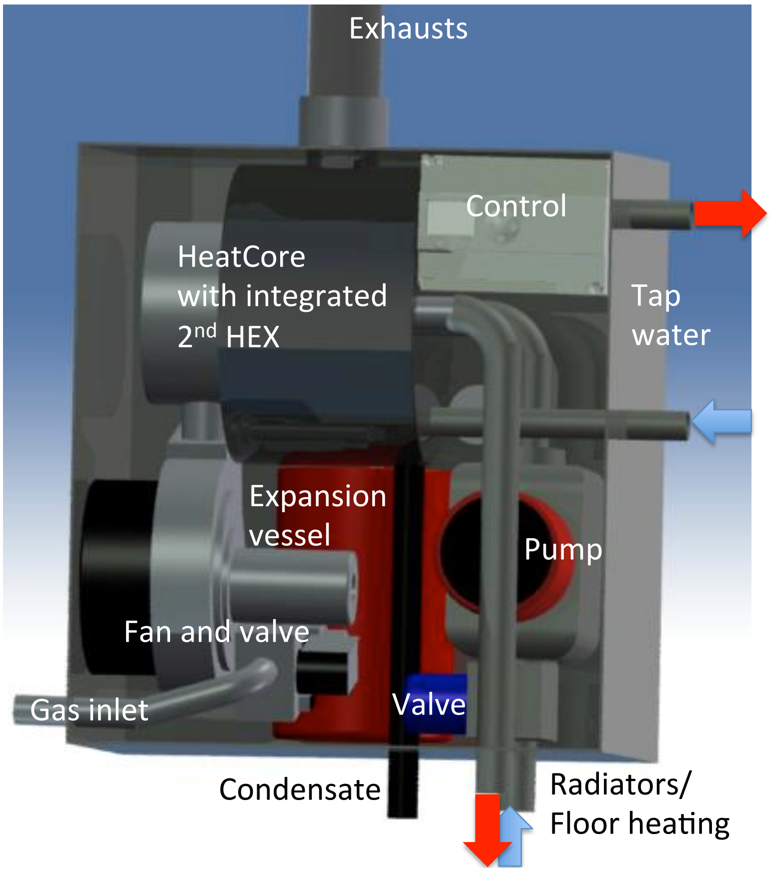

Figure 9 *CAD-packaging of a highly integrated boiler system comprising the HeatCore-module with an integrated 2nd heat exchanger (380 x 260 x 350 mm – 34 l)*

The boiler unit has been successfully commissioned and evaluated and relevant combustion data for the HeatCore-module are discussed in the next sections.

7. Possible thermo mechanical issues and evaluations

The main item in the technical risk portfolio is associated with thermo-mechanical fatigue in the heat exchanger section adjacent to the combustion chamber. The individual plates are joined to each other in this section, preferably via welding. Consequently, there exists a flanged section, which might get hot during operation due to poor cooling. If the flange tip gets too hot in relation to the cooled section, cracks may form following a certain number of thermal cycles. The maximum temperature allowable will depend on a number of geometric parameters and the predicted number of thermal cycles during the lifetime.

To evaluate these phenomena, the flange tip temperatures were measured in a specially designed rig during operation. Temperatures were measured at certain positions by means of thermocouples and by thermography. The length of the flange tip was varied and compared with CFD-calculations for the heat transfer in the system.

Figure 10 shows the rig for flange tip temperature measurements together with a thermal image obtained for one plate type. The correlation between thermocouple measurements and results from thermal imaging was found to very very good, which can be seen in Table 2 below.

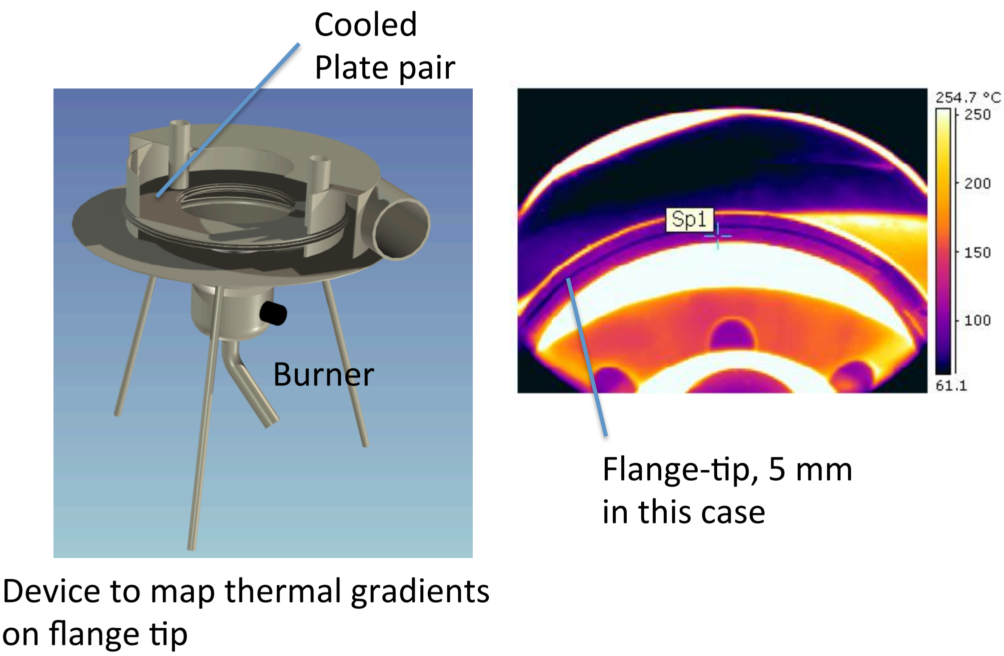

Figure 10 Rig for measurement of thermal gradients and a thermal image Flange temperature around 170°C for a 5 mm flange tip.

The experimental data were also correlated to theoretical CFD-simulations. In these simulations, various geometric features could be investigated as well as the choice of construction material. Moreover, the effect of the process conditions (lambda value and load) can be investigated. It was found that the length of the flange section should be minimized and that aluminium would give great advantages over steel. The material thickness will also affect the situation to some extent. Figure 11 shows a typical CFD-result, were different flange lengths are compared. It is obvious that there is a huge merit in reducing the length of the flange. The simulations take all relevant heat transfer processes into consideration, i.e. convection and conduction in the gas, the water and the metal substrate, respectively.

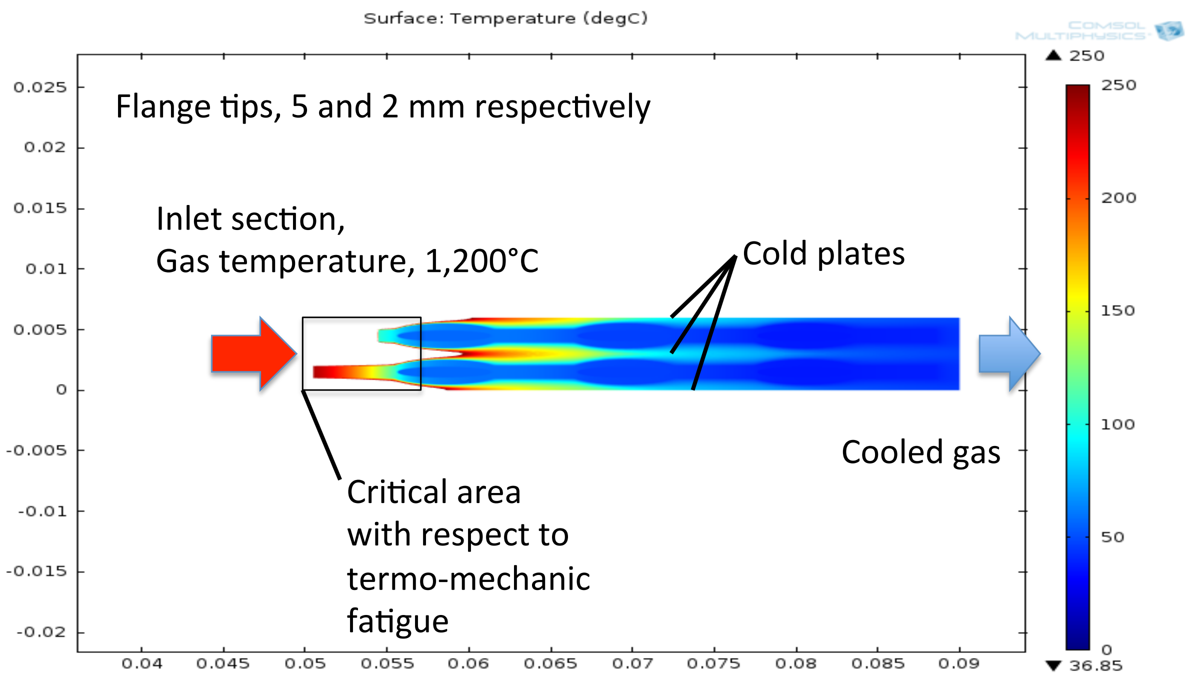

Figure 11 Calculated flange temperatures during operation at rated load (2 and 5 mm flange tips shown).

The temperature distributions were then imported into a strength calculation module to evaluate the stresses in the joint. Additional calculations were also performed manually for a disk.

Table 2 below summarizes results concerning stresses found in FEA-analysis (FEA=finite element analysis) and by manual calculations (thin disc under thermal load). Various flange lengths have been studied and the temperatures have been measured by means of thermocouples attached to the flange tip, and by thermography. The temperature levels have also been analysed by means of CFD-modelling. The water temperature adjacent to the flange was around 60°C.

Table 2 Stress levels expected in the joint between plates adjacent to the combustion chamber when the flange length is varied. Stresses calculated according to von Mise.

Temperature (°C)	< 1 mm	2 mm	3 mm	4 mm
TC-measurements	60-70	90-100	140	160-170
Termography	50-70	Ca. 100	130	160
CFD-calculations	68	101	142	187
Stresses (N/mm^2)	**(von Mise)**			
Stress analysis	82	162	235	313
CFD/FEA	59	147	258	380

It is obvious that flange-tip temperatures in excess of 120°C will give rise to relatively high stresses, which might harm the construction following a large number of cycles. Diagrams showing the relation between acceptable stresses and number of cycles (Wöhler diagram) are readily available for a large number of materials [e.g. 40, 41]. Figure 12 below shows typical results obtained for austenitic steel and aluminium, respectively.

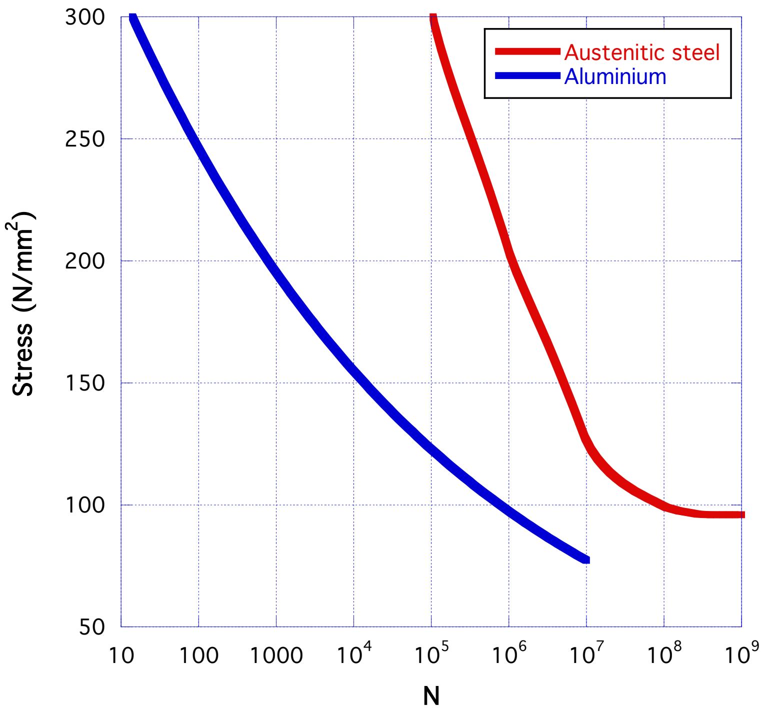

Figure 12 Wöhler diagram for austenitic steel and aluminium, where N is the number of cycles [40, 41]

Whereas there exists a limit where steel will survive independent on the number of cycles, the same situation does not apply to aluminium. The minimum number of thermal cycles in a boiler installation is around 300,000. If we include a safety factor of 2, we end up with at least 600,000 cycles. According to the diagram, the maximum allowable stress for austenitic steel should then be around 200 N/mm^2. The corresponding asymptotic value is around 95 N/mm^2. For aluminium the limit corresponding to 600,000 cycles is around 110 N/mm^2 but no asymptotic value exists.

From the stress calculations, it is obvious that flange temperatures exceeding 120°C will be detrimental and should be avoided. The flange tip length must obviously be less than 2 – 3 mm to survive the rated load. It is extremely difficult to verify these kinds of data since an accelerated cycling test in a real unit will take a year or more. Consequently, a method for rapid cycling was necessary to develop.

The rapid cycling rig is based on resistive heating of the flange tip and rapid cooling by means of compressed air. By using this method it was possible to generate up to 6 thermal cycles each minute (80 ⇔ 120°C). In tests with higher peak temperatures, the cycling rate was somewhat slower, e.g. 4 thermal cycles per minute between 100 and 200°C. A number of cycling tests were performed between different temperature levels and a cycling test covering 150,000 full thermal cycles was performed between 80 and 120°C to mimic a realistic case during operation. The plate assembly was investigated for leakage every 50,000 cycles. No leakage could be detected following 150,000 full thermal cycles. When the upper temperature level was increased to 200°C, we indicated increased leakage rate following 50,000 cycles, which also was expected from theory.

The rapid cycling rig might consequently be used for evaluating thermo-mechanical fatigue in this application.

Apart from the stresses/displacements due to thermal gradients there are also displacements which originates from the static pressure load on the water side (typically 3 bar(a)). Figure 13 below shows the displacements (exaggerated) for a plate under under static and thermal load. Thus, it is important to join the plates also in the field of the plate structure in order to avoid significant displacements.

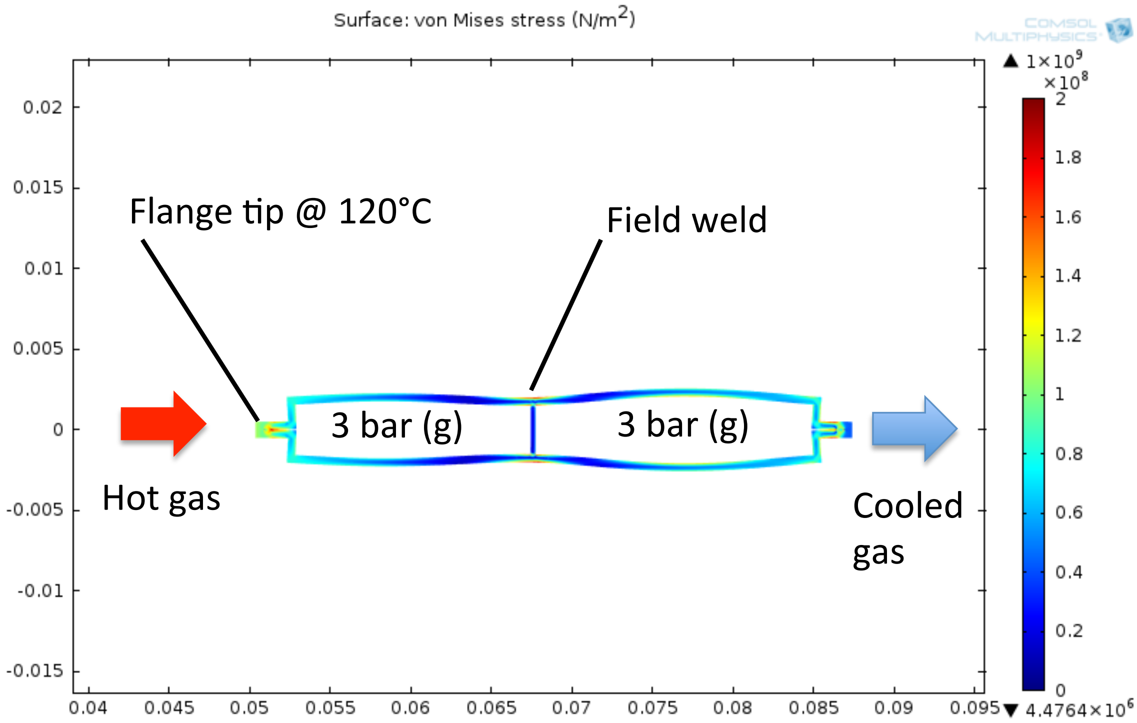

Figure 13 Displacement of the plate structure (cross section) under thermal + static load (3 bar(g)). Displacement exaggerated. Maximum displacement in reality is below 50 µm.

The experimental and theoretic studies of thermal gradients have resulted in valuable information for refinement of the plate design close to the combustion chamber. The correlation between experimental results and theoretically derived data is generally good. The temperature data has been interpreted by means of strength calculations (manually and by FEA-methods) and indicate a reasonable window for the flange temperature. This temperature window has then been verified by a rapid thermal cycling test.

Even if the design background seems to rely on a firm foundation, it is important to perform long-term tests in the real chemical environment. There is a possibility that chemical and thermal phenomena might interact to create a more difficult environment for the mechanical structure. Such tests will be performed, possibly in collaboration with boiler manufacturers or together with a research institute.

8. Performance

The HeatCore-modules constructed in this project have been experimentally evaluated in a number of tests. Natural gas and air were mixed upstream the HeatCore unit and was then led into the unit. Ignition was performed by a glow plug and within a few seconds the combustion process was shifted from blue flame combustion into hybrid combustion. Water was led through the unit at a flow rate of approximately 1 m^3/hr. The increase in water temperature over the unit should be around 20°C at rated load (ca 20 kW). The inlet temperature of water could be varied in order to evaluate the thermal efficiency for various modes of operation. Flue gas temperatures as well water temperatures (inlet and outlet) were monitored to enable calculations of the heat output. Thermal images were taken on the unit during operation to detect possible hot spots and to indicate overheating of the inlet manifold to the burner. Emission data were collected by means of NDIR (CO_2, CO and UHC), FID (UHC) and an electrochemical device (CO, NO_x and O_2).

Figure 14 shows a thermal image of the HeatCore-unit under operation at rated load. The inlet manifold is not overheated and the flanges are kept at a uniform temperature level (no gradients). If the gas-or water flow was poorly distributed, it should be possible to detect such abnormalities by thermal imaging.

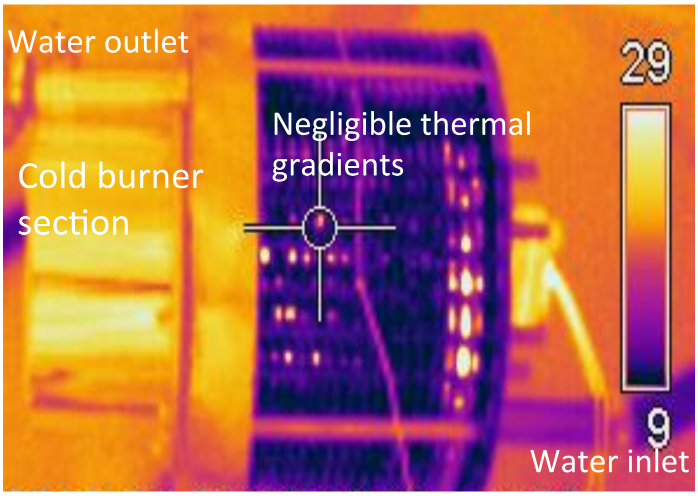

Figure 14 Thermal image of the HeatCore-unit under operation (15-20 kW). Cold city water (10°C) is used as coolant. Air/gas-inlet temperature is at ambient levels.

Table 3 summarizes relevant combustion data obtained for natural gas type H in the domestic HeatCore-unit. As can be seen by the values, we obtained very high thermal efficiencies at inlet temperatures below 30°C. The NO_x-emissions are low and within expected limits whereas the CO-emissions still are a bit too high. The high CO-emissions are attributed to super cooling of the combustion zone. This aspect is affected by the exact design/orientation of the catalyst cartridge. By minor modifications in this part, we expect to reduce these emissions to value between 50 and 100 ppm at rated load. The excess air ratio can be varied between 1.2 and 1.4 (1.5) but best results with respect to emissions are generally reached around 1.35.

Table 3 Performance data for the domestic HeatCore run with NG-H (inlet-temperature of water ca. 10°C).

Q (kW)	NO_x (ppm)	CO (ppm)	O_2 (%)	Cond g/kWh	Tg – Tc (°C)	η_{LHV} (%)
5 kW	15	<30	7.0	140	5	109
10 kW	12	40	7.0	134	7	108
15 kW	16	80	6.1	131	15	108
20 kW	12	130	6.5	127	19	107
25 kW	12	170	6.3	118	23	107

There are a number of relevant standards and requirements associated with emissions. The relevant norm, describing emissions is SS-EN 15502-1:2012 [42]. There are also other local and optional standards, which many boiler manufacturers try to adapt to (e.g. the Hannover norm, Svanenmärkning etc). According to EN 15502-1:2012, the maximum acceptable CO-level is 0.10% (1,000 ppm). For the NO_x-emissions, the boilers are divided into five classes, where the most stringent class (class 5) allows 70 mg/kWh (35 ppm @ 3% O_2). From this perspective, the HeatCore-unit complies with the regulations but further improvements concerning the CO-emissions are required from a market perspective. Typically, the expectation is to arrive at CO-levels below 100 ppm at full load.

A number of different gas qualities were investigated in the non-condensing HeatCore unit constructed for leisure applications (5 – 10 kW). The combustion section of this unit is identical to the combustion section in the domestic HeatCore. The tested gas qualities have been inserted into a Delbourg diagram showing the Heating value and the relative density of the fuel gas. The gas compositions and some key data are given in Table 4. In addition to natural gas (L/H) and LPG, we have tested digestion gas with various amounts of carbon dioxide and pyrolysis gas compositions provided by Peak Eco Energi AB. Peak Eco is currently developing and evaluating systems for production of fuel gases from various waste sources, like sludge. We have also tested the unit with town gas compositions (reformate gas). Two different town gas compositions were tested: 8a) – Reformate type town gas form light naphtha reforming where LPG has been added to increase the LHV (e.g. Malmoe until 1985), and 8b) – town gas where methanisation is used (e.g. Stockholm until 2011).

able 5 shows some combustion data obtained for the various gas qualities at around 6 – 8 kW thermal heat output. The emission footprint is low and the combustion is complete and without backflash phenomena for all tested qualities. This result highlights the fuel versatility of catalytic combustion. With a conventional flame combustor, it should have been necessary to adjust nozzles and burner head dimensions according to the fuel quality. With catalytic combustion no such adjustments are necessary.

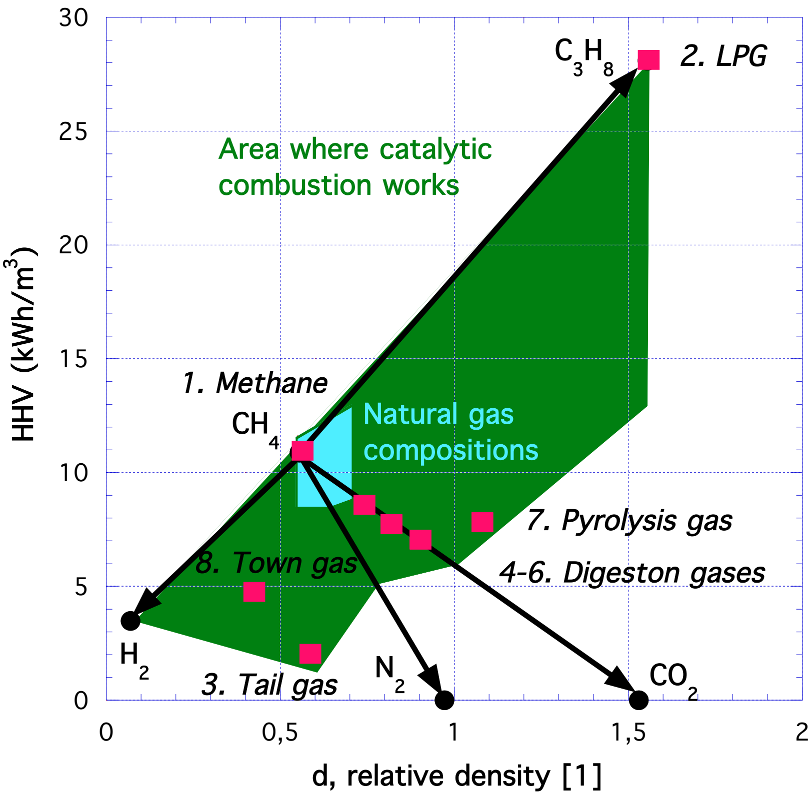

Figure 15 Tested gas qualities inserted into a Delbourg diagram

Table 4 Investigated gas compositions and lower heating value (LHV)
*) Tail-gas compositions can vary due to fuel-cell type and utilization factor.

	CH_4(%)	CO(%)	CO_2(%)	H_2(%)	LPG(%)	LHV(kWh/nm^3)
1. Pure methane	100	-	-	-	-	9.8
2. LPG	-	-	-	-	100	26.3
3. Tail gas *)	<1	-	45	54	-	1.7
4. Digestion gas 1	70	30	-	-	-	6.9
5. Digestion gas 2	65	35	-	-	-	6.4
6. Digestion gas 3	60	40	-	-	-	5.9
7. Pyrolysis gas	15	15	45	7.0	18	6.7
8a. Town gas, Malmoe until 1985	7.0	3.0	17	67	6.0	4.4
8b. Town gas, Stockholm	30	2.0	13	54	0.0	4.6

Table 5 Results obtained in experiments with varying gas quality @ 6 - 8 kW.

	O_2(%)	CO (ppm)	NO_x(ppm)	UHC(ppm)
1. Pure methane	7.0	35	11	<10
2. LPG	7.0	65	16	<10
3. Tail gas *)	3.0	n/a	0	n/a
4. Digestion gas 1	6.9	64	9	<10
5. Digestion gas 2	6.9	59	8	<10
6. Digestion gas 3	6.9	56	7	<10
7. Pyrolysis gas	6.9	49	8	<10
8a. Town gas	7.3	0	1	<10
8b. Town gas	6.8	0	2	<10

The experimentally obtained thermal efficiencies have been evaluated by CFD-modelling to analyse the necessary number of plates for various heating effects, see Table 6 below. To reach the theoretic efficiency at full load (25 kW), the HeatCore-unit should be fitted with 45-50 plates. Values are given for an air-excess ratio of 1.35, an air-inlet temperature of 20°C and a RH of 40%. If it is acceptable to run under slightly less efficiency during tap-water heating, the number of plates could be reduced. Adding a few plates more will however only marginally increase the geometric measures and cost. Theoretical values are reached for an infinite number of plates, as shown in the table.

The theoretical calculations always give slightly better results since perfect and uniform distribution of flue gas and water are taken for granted. By using the system efficiency factor, derived from this comparison, expected efficiencies might be calculated from theoretical data.

Table 6 Efficiencies (%) for various HeatCore configurations. Values given at 10 and 25 kW thermal effect for various water temperatures. Geometric data are given as well as cost predictions.

No. of plates	w (kg)	V (litre)	Rel. cost	η (30/50)	η (60/80)
20	2.3	2.4	0.70	106.2	97.8
				95.6	94.5
30	2.9	2.9	0.85	107.3	97.9
				97.9	95.8
40	3.5	3.5	1.0	107.3	97.9
				104.9	97.4
50	4.1	4.1	1.15	107.3	97.9
				107.0	97.8
60	4.7	4.6	1.30	107.3	97.9
				107.2	97.9
∞	n/a	n/a	n/a	107.3	97.9

The thermal efficiency will normally decrease somewhat with the thermal load. Figure 16 show the expected efficiency relation (water temperatures between 30 and 50°C) as a function of the load. The influence of the number of plates is also highlighted in this diagram. To reach peak efficiencies all over the load window, some plates might preferably be added to the heat-exchanger body. As an alternative it is possible to decrease the pressing depth on the gas side to enhance the heat transfer capacity. The drawbacks in doing so are associated with increased pressure drop and possible clogging by condensate.

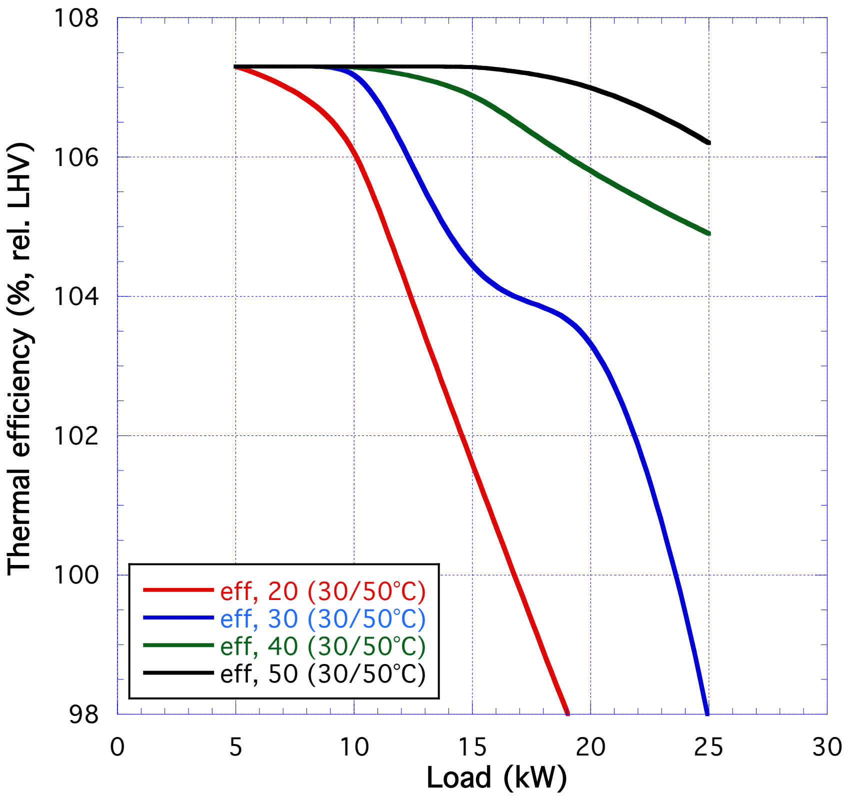

Figure 16 Thermal efficiency as a function of the load (30/50), forecasted by CFD-simulations. Simulations have been performed for various number of plates. Theoretical limit was 107,3% at these conditions.

The temperature levels in the water circuit will affect the thermal efficiency. If the temperature is increased, the thermal efficiency will decrease due to poor condensation and higher flue gas temperatures. Figure 17 shows experimental data obtained at 10 and 20 kW together with calculated data. It is difficult to achieve higher thermal efficiencies than 100% (based on LHV) at inlet temperatures exceeding 50°C, as indicated by the diagram. The correlation between experimental and theoretical data is generally very good.

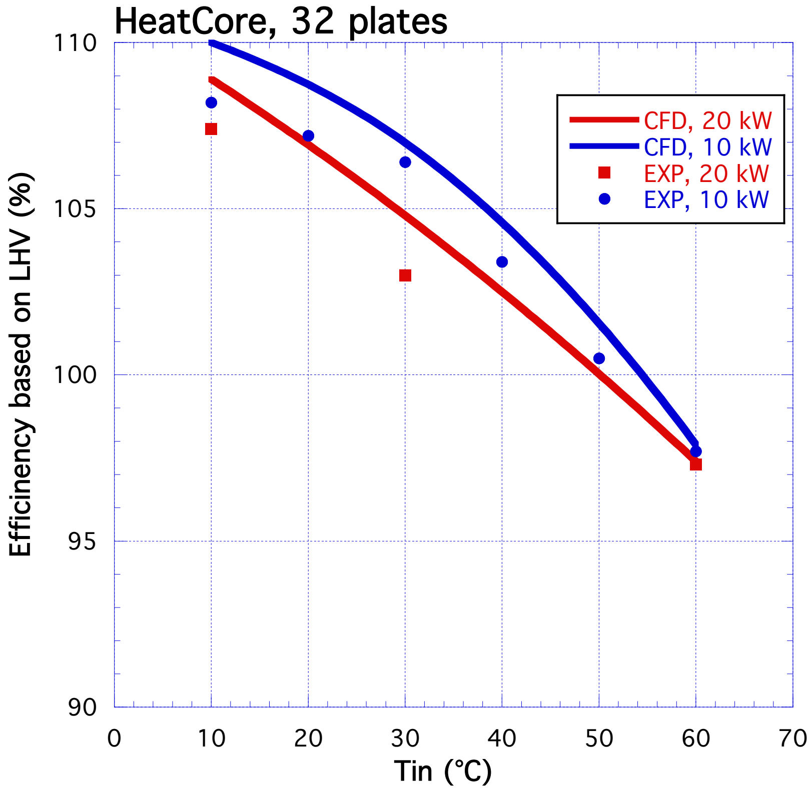

Figure 17 Thermal efficiencies at 10 and 20 kW vs inlet temperature levels on the water side in the HeatCore

The requirement concerning useful efficiencies are described in SS-EN 15501-1:2012 [42]. For condensing boilers the following relationships are presented:

Nominal load: $\eta \geq 91 + \log_{10}(P_n)$, P_n (nominal load) in kW
Part load: $\eta \geq 97 + \log_{10}(P_i)$, P_i (normally nominal load) in kW

Some boiler manufacturers present data for nominal load and for 30% load [e.g. 43,44]. The nominal efficiency (30/50°C) is generally around 105% whereas it reduces to around 97.5% at non-condensing conditions (60/80°C). At 30% load (30/50°C) most modern boilers show efficiencies above 107%. Indeed, the efficiencies found in boilers on the market are generally much higher than the values given by SS-EN 15501-1:2012. DIN 4702-8 is another way of determining the efficiency by generating an arithmetic mean of measurements at various loads (13, 30, 39, 48 and 63%) and heating circuit temperatures [45].

The NO_x-emissions decrease with increasing excess-air ratio whereas the CO-emissions increase. This phenomenon is explained by the variation in combustion temperatures at different excess-air ratios. In addition to this, the residence time in the combustion zone as well as the transformation between various modes of combustion may play a significant role. In Figure 18, the NO_x-emissions are shown at various loads and excess-air ratios. In order to achieve CO-levels below 100 ppm, however, the excess-air ratio should not go above 1.4.

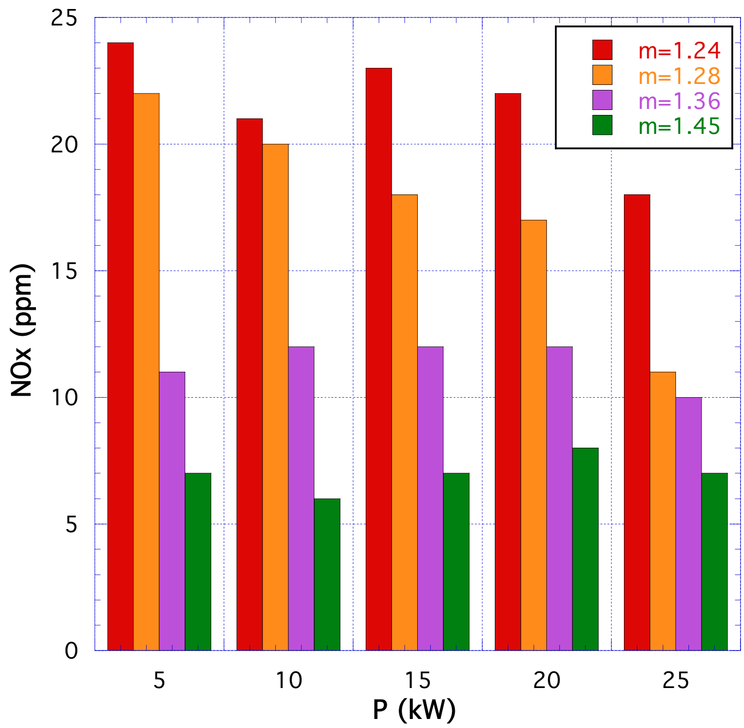

Figure 18 NO_x footprint as a function of the load and the excess air ratio (given as m in the legend)

Emissions of unburned hydrocarbons are generally not a problem since the methane concentration in the flue gases is below the detection limit (a few ppm) under stable operation. During start-up, however, there is a risk for increased emissions of hydrocarbons. Figure 19 shows a typical UHC-peak during s/u of the HeatCore-unit. The emitted amount of hydrocarbons is still very small, as can be calculated by integrating the peak. The amplitude of the peak will , however, depend on the start-up sequence (from several thousand ppms down to less than 100). It is thus important to tune the start-up sequence concerning the ignition delay and the ramp-up speed. The UHC-emissions during shut/down will mainly depend on the valve characteristic. To minimize these transient UHC-emissions, it is important to use a wide modulation window and to avoid repeated start-ups and shutdowns.

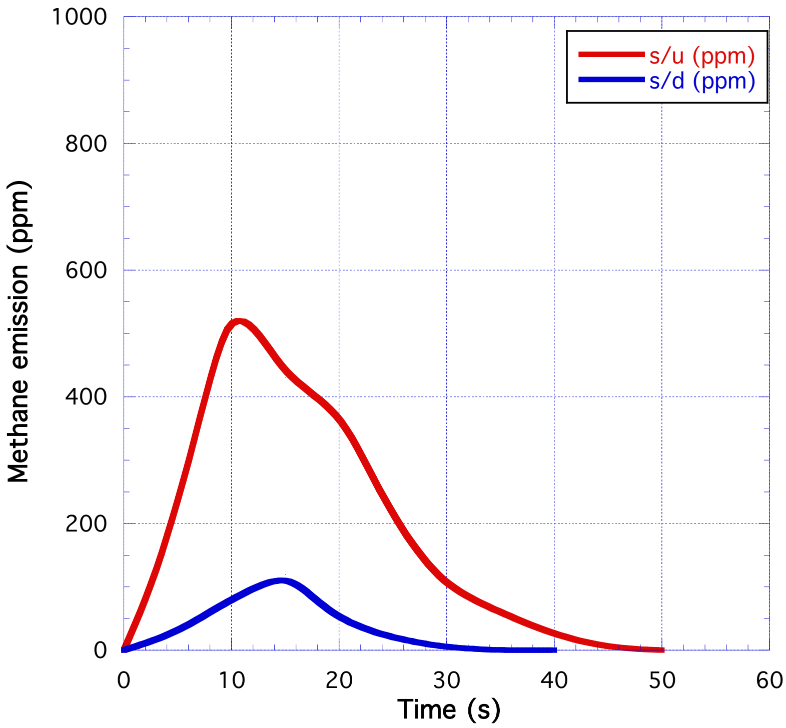

Figure 19 Typical UHC-emissions during start-up (s/u) and shutdown (s/d).

Exactly as for thermal efficiencies, there exists a number of ways to calculate and represent emission footprints. As previously mentioned SS-EN 15502-1:2012 gives limits for both CO- and NO_x-emissions [42]. These emission limits are, however, relatively high and normally much higher than what can be found in modern installations. Local and optional requirements are normally much more stringent [27]. The Nordic Svanen mark requires NO_x-emisssions to be below 35 ppm (3% O_2) whereas the CO-emissions should stay below 16 ppm (3 % O_2) [28]. According to DIN 4702-8, the emissions are calculated as the arithmetic mean of data collected at a number of load points (13, 30, 39, 48, 63 and 100%).

The combustion experiments clearly demonstrate the fuel versatility of the HeatCore concept and the possibility to reach high thermal efficiencies and low emission footprints. Continued optimization work should focus on measures to reduce the CO-emissions further and on design improvements to minimize the number of plates in the heat-exchanger body. These activities will involve modifications of the catalyst cartridge as well as actions to improve the flow distribution and the heat transfer capacity in the plate structure, possibly by a decreased pressing depth.

9. Scalability

As previously mentioned, the demands in various application fields vary with respect to the fuel choice, the heat output and the thermal efficiency. The HeatCore-module discussed so far is intended for the domestic boiler market (5 – 60 kW). The plate geometry and pattern has been designed to facilitate effective condensation in one step.

In the leisure segment the heat effect is lower, typically 2 – 10 kW and condensation should be avoided due to difficulties to handle the drained water. The units should be fuelled with LPG and/or liquid fuels like ethanol, kerosene or diesel. A non-condensing HeatCore module for LPG (5-10 kW) was designed, constructed and evaluated in the project. A comparison between the domestic HeatCore and the leisure-type HeatCore is shown in Figure 20 below. The non-condensing HeatCore is more compact and is based on another plate geometry and pattern. It is also possible to replace the LPG burner head with a multi-fuel burner head for operation with liquid fuels. The heat exchanger part of the unit will be unchanged and only the burner section needs to be replaced. Results obtained in the non-condensing HeatCore are presented in Table 3 below.

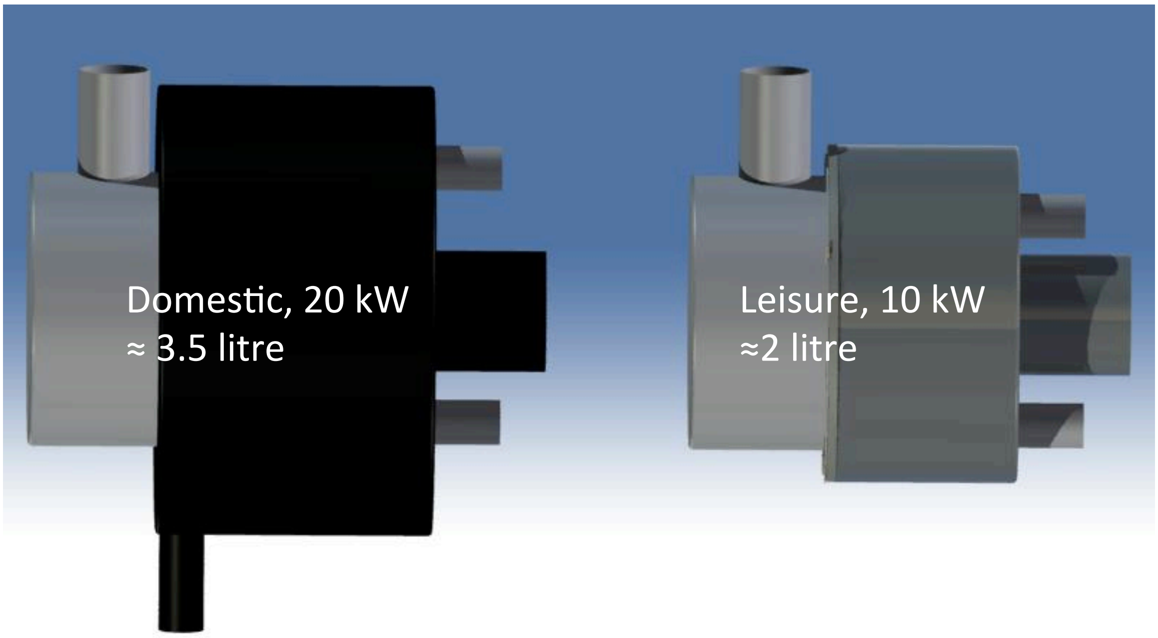

Figure 20 Comparison of 20 - 25 kW domestic HeatCore and a 10 kW non-condensing HeatCore for leisure applications

Table 3 Evaluation results from the 10 kW LPG non-condensing HeatCore.

Load (kW)	O_2 (%)	CO (ppm)	NO_x (ppm)	T_{exh} (°C)
1.2	7.0	3	2	30
2.4	7.1	11	8	50
4.5	7.0	49	19	75
6.3	7.0	61	16	112
8.2	7.0	72	16	133
10.1	7.0	130	15	172

The excess air ratio was around 1.4 in these tests and the cooling was performed with cold tap water (10°C). The HeatCore-module comprised 20 plates in this case. The CO-emissions and the exhaust temperatures increase monotonously with the load. Additional experiments with hot water at the inlet (ca 60°C) showed that condensation could be avoided all over the load window. The exhaust temperatures at higher loads (>5 kW) were however only marginally affected (5 – 10°C). The heat effect was calculated from the water flow rate and the temperature difference between the inlet and the outlet.

Based on the non-condensing plate concept, it is possible to scale these units from a few kW (10 plates) up to 25 kW (50 plates). The burner head will be unchanged apart from minor modifications in the catalyst cartridge.

The liquid burner head needs an appropriate atomization-and mixing device upstream the catalyst and a special ignition source. Catator has developed a special combustion supported atomization technique, previously used in fuel processors for logistic fuels [48]. Figure 21 shows how the HeatCore-module can be integrated with such a device. It is possible to use this burner head also for fuel gases like LPG and natural gas even if the design is more complicated than the burner head for only fuel gases.

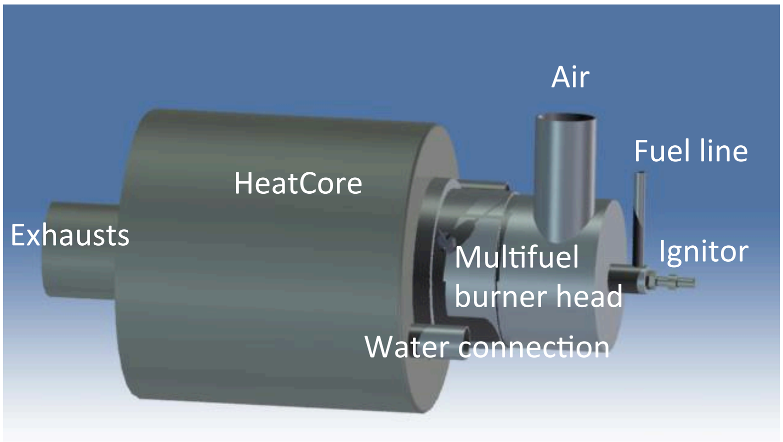

Figure 21 HeatCore module for logistic liquid fuels like ethanol, kerosene and diesel.

In the project we have also investigated the possibility to design industrial boilers based on the HeatCore-concept. In order to reach higher effect outputs it was necessary to design a new plate with an increased diameter. Simultaneously, it is of importance also to increase the size of the combustion chamber to enable reasonable residence times for completion of the combustion processes. Moreover, the amount of combustion catalyst needs to be increased approximately in relation to the rated heat output. We investigated HeatCore-modules with a plate diameter in the span between 250 and 400 mm. Such plates can easily be formed in a conventional pressing unit at moderate pressures. The intention is to use between 30 and 100 plates in series, which give corresponding effect outputs between 50 and 400 kW (with full condensation). It is also possible to put several units in parallel (cascade units). Figure 22 below shows a 250 kW unit together with relevant geometric data. In addition this unit is compared with the standard domestic HeatCore and the non-condensing unit for LPG, described above.

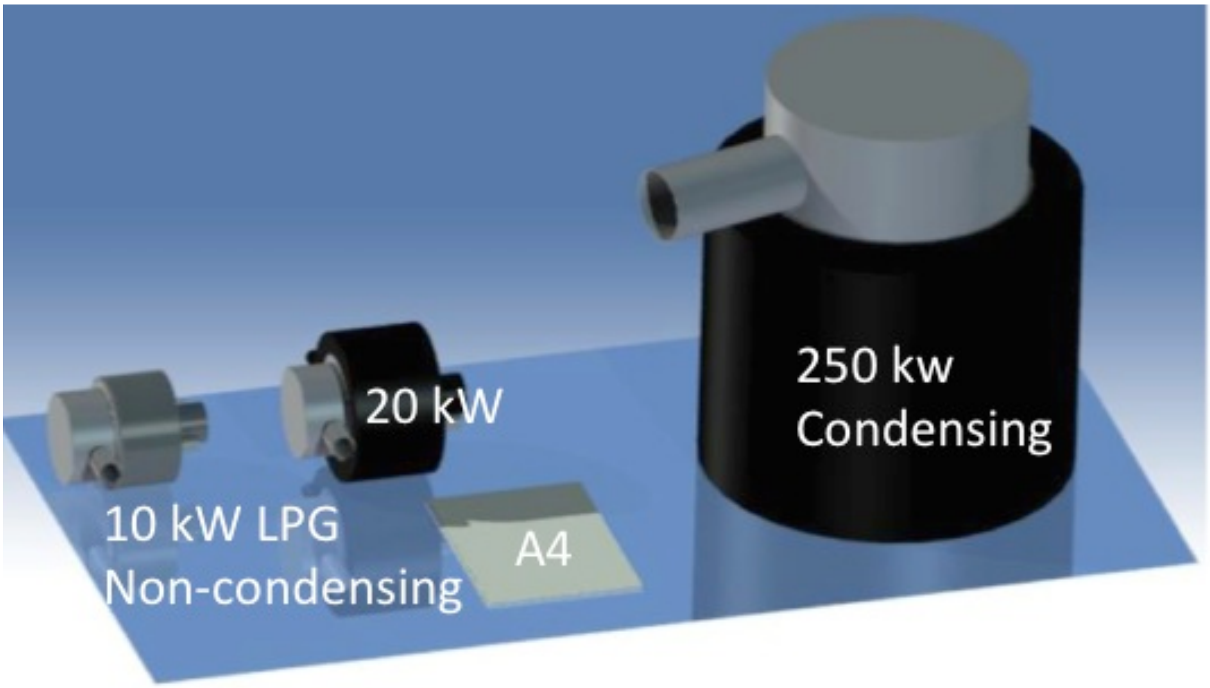

Figure 22 Industrial HeatCore for an effect output of 250 kW

The industrial HeatCore has not been constructed and evaluated but the intention is to conduct such studies in a follow-up program to this project. The evaluation of the unit will then be conducted in close collaboration with an industrial boiler manufacturer.

The investigation concerning scalability has verified the great potential of the plate-type heat exchanger concept in these applications. It is perhaps not a surprise that such a concept can show this degree of scalability. This feature is typical for plate-type heat exchangers.

10. Continued activities

Even if a number of important features have been verified in this project there are still a number of question marks to be handled. The conducted studies give great confidence concerning problems with thermo-mechanical fatigue. Possible problems with corrosion should be possible to handle – at least on the paper – since the structure has a homogenous material composition. However, as stated by several boiler manufacturers, corrosion is an extremely difficult area where accurate prediction models for long-term effects are lacking. The combustion environment is also complicated with respect to thermal and chemical phenomena. A number of parameters can contribute to give rise to a corrosive environment. These effects can only be studied in long-term tests even if some boiler manufacturers have developed accelerated tests where predictions covering 15 years can be handled in a year. Indeed, it is of fundamental importance to long-term reliability in these applications.

Integration of more functions into the HeatCore-module (e.g. 2nd heat exchanger for tap water heating) is possible and should be studied. Such measures would facilitate an even more compact design approach.

A long-term test is thus mandatory and should be conducted by a third party, e.g. a boiler manufacturer or a suitable institute. This evaluation should also include tests according to relevant standards, e.g. efficiency calculations (on a year basis) and the average environmental footprint.

A number of boilers including HeatCore-modules should be installed and tested in a field trial, possibly in collaboration with a boiler manufacturer. These installations should reflect various heating needs and various geographic locations since the air-and water quality might vary. In some areas the chlorine activity is high, which can accelerate any corrosion phenomenon. Also the gas quality might vary with respect to trace components and type/concentration of odorant.

It is also planned to construct and to evaluate an industrial HeatCore-module together with a relevant system manufacturer. The module should have a thermal capacity of at least 200 kW and might comprise one or several HeatCore-modules (cascade coupled).

11. Conclusions

The conducted project has demonstrated and verified a number of capabilities of the HeatCore-module. It is indeed possible to build an extremely compact boiler cabinet including not only the HeatCore-module itself but also all necessary balance-of-plant components and the control- and safety system. The volume of the entire boiler cabinet could be decreased by almost 40% compared to leading brands on the European market, already following the first design iteration. Further refinement and integration should facilitate an even more compact system architecture.

Decreased volume and weight come with substantial energy- and environmental savings throughout the entire value chain, i.e. in material handling, production, transportation, assembly and installation.

The domestic boiler market is extremely big and more than 20 million boilers are sold each year globally. Only in Europe, the market size is around 7 million units per year. In Europe, there are about 10 relevant system manufacturers and most of these buy the combustion packages (primary heat exchanger) from external sources. Some of the manufacturers have some in-house production, usually based on casted aluminium structures. There are only a few external suppliers, which should indicate that the competition in this field is poor with a close to monopoly market structure. There is a great interest within the boiler industry to find innovative solutions with high effect density, high efficiency and low emission footprints. Features like scalability and fuel flexibility are other important selling points.

The HeatCore-module can reach the demands concerning geometry (size and weight), efficiency and emission footprint. In addition, the deign shows a high degree of scalability and units ranging from a few kW thermal output to several hundred kW can be produced according to the same principle. Thus, the concept can be used not only in domestic boilers but also in leisure applications and in industrial heating. This study also verifies the great fuel flexibility offered by catalytic combustion with fuel qualities ranging from natural gas and LPG to low-BTU gases like digestion gas, pyrolysis gas and town gas (reformate).

The HeatCore module comprises a round heat exchanger body tied to a catalytic burner head. Burner heads are available not only for fuel gases but also for liquid fuels like ethanol, kerosene or diesel. The HeatCore-module has been designed for production and product cost calculations indicate a cost level where substantial market penetration should be possible in various market segments.

The technical risk portfolio has been decreased as methods to analyse, forecast and circumvent thermo-mechanical failures have been evaluated and verified. A method for accelerated thermal fatigue test has been developed in the project and the assembly has survived more than 150,000 full thermal cycles without any problems with crack formation.

The intention is to formulate a follow-up project to facilitate third-party evaluations and long-term testing. In addition a HeatCore-unit for industrial applications will be constructed and evaluated.

12. Literature

1. *Utveckling av brännare för katalytisk förbränning av naturgas*, Värmeforsk rapport no. 396, J. Brandin, F. Ahlström, 1991.
2. *Utveckling av katalytisk brännare*, Värmeforsk rapport no. 475, F Ahlström, 1993.
3. *Katalytiska värmeväxlare för industriella tillämpningar*, Värmeforsk rapport no. 496, F. A. Silversand, T. Hargitai, 1994.
4. *Katalytisk brännare för emissionsreduktion i befintliga fastighetspannor: slutrapport*, Statens Råd för Byggnadsforskning (Byggforsk), Rapport 920698, T. Hertzberg, J. Brandin, T. Hargitai, F. Silversand, M. Näslund, 1994.
5. C. N. Satterfield, *Heterogeneous Catalysis in Practice*, McGraw-Hill, New York, 1980, p1
6. P. Gélin and M. Primet, Applied Catalysis B:Environmental 39 (2002) 1-37.
7. J. G. McCarty, R.H. Lamoreaux and M.A. Quinlan, Proc. of. 1989 International GasResarch Conference, Tokyo 6-9 nov 1989, vol III, 232-41.
8. S. Seimanides and M Stoukides, J. Catal., 98:2 (1986), 540-9.
9. *Combustion of methane over a Pd-Al2O3/SiO2-catalys, catalyst activity and stability*, A. Fredrik Ahlström-Silversand and C.U.I Ingemar Odenbrand Applied catalysis A:General, 3677, 1 – 19 (1997)
10. H. Arai and M Machida, Catalysis Today, vol. 10 (1991) 81.
11. J.S. Church, N.W. Cant and D.L. Trimm, Applied Catatlysis A:General 101 (1993) 105.
12. *Catalytic abatement of CO- and UHC-emissions from Gas Fuelled Engines*, SGC rapport nr. A22, F. Silversand, 1999.
13. *Thermally sprayed wire-mesh catalysts for the purification of flue gases from small-scale combustion of bio-fuel – Catalyst preparation and activity studies*, A. Fredrik Ahlström-Silversand and C.U.I Ingemar Odenbrand Applied catalysis A:General, 3678, 1-25 (1997)
14. *Modelling catalytic combustion of carbon monoxide and hydrocarbons over catalytically active wire meshes*. Fredrik Ahlström-Silversand and C.U.I Ingemar Odenbrand, Chemical Engineering Journal 3431, 1 – 12 (1999)
15. *Catalytic burners in larger boiler installations*, SGC rapport no. 201, F. Silversand, M. Persson, 2009.
16. K. Beebe, K. Cairns, S Nickolas, V. Pareek, J. Schlatter and T. Tsuchida, *Development of catalytic combustion technology for single-digit emissions industrial gas turbines*, Proc. of the 4th IWCC, San Diego, April 14-16 (1999).
17. H- Sadomori, T. Tanioka and T. Matsushisa, *Development of a high-temperature combustion catalyst system and prototype catalytic combustor turbine test results*, Proc. Int. Workshop on catalytic combustion, Tokyo, April 18-20, Catalysis Society of Japan, 1994, p. 158.

18. *Catalytic Combustion in Energy Production and Environmental Protection*, Fredrik Ahlström-Silversand, Ph.D.-thesis, Lund Institute of technology, ISRN LUTKDH/TKKT—96/1040--SE, Lund 1996.
19. *Catalytic heat exchangers – a long-term evaluation*, SGC rapport no. 140, F. Silversand, 2003.
20. EN 483, *Gas-fired central heating boilers. Type C boilers of nominal heat input not exceeding 70 kW*.
21. EN 625, *Gas-fired central heating boilers. Specific requirements for the domestic hot water operation of combination boilers of nominal heat input not exceeding 70 kW*.
22. EN 677, *Gas-fired central heating boilers. Specific requirements for condensing boilers with a nominal heat input not exceeding 70 kW*.
23. EN 437, *Test gases. Test pressures. Appliances categories*.
24. EN 297: *Gas fired central heating boilers. Type B11 and B11BS boilers fitted with atmospheric burners with a heat input not exceeding 70 kW.*
25. RAL-UZ 61 – Blue Angel, *Low-emission and energy-saving gas condensing boiler*.
26. SS-EN 15502-2-1:2012, *Gas-fired central heating boilers-Part2-1: Specific standard for type C appliance and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1 000 kW*.
27. *Energimätning av villagaspannor*, M. Näslund, DGC rapport no. 199, February 2009.
28. *Svanenmærkning af Kedler og Brændere till flydende og gasformigt brændsel*, Version 5.0.
29. *Development of a novel catalytic burner for natural gas combustion for gas stoves and cooking plate applications*, Anna-Karin Jannasch, Fredrik Silversand, Marc Berger, Davis Dupuis, Emmanuel Tena, Catalysis Today, 117, 433 (2006).
30. Ecodesign of EuP: Lots 1 & 2, CH-boilers and water heaters, information provided by Rene´ Kemna, VHK, the Netherlands
31. Web address: dgc.dk
32. Web address: Giannoni.fr
33. Directive 90/396/CEE - GAD
34. Directive 92/42/CEE – Efficiency directive
35. Web address: vaillant.de
36. Web address: bosch.de
37. Web address: baxi.co.uk
38. Web address: ferroli.it
39. Web address: veissmann.de
40. Tryckkärlsnormer 1987, Tryckkärlskommissionen, ISBN 91.85254-00-2, Stockholm 1987, p. 243-47.
41. EN 1999-1-3, *Fatigue of aluminium structures.*
42. SS-EN 15502-1:2012: General requirements and tests
43. Data for Nuvola3 Comfort HT (Baxi)
44. Data for Remeha Gas 110 Eco
45. DIN 4702-T8

46 *Varierande gaskvalitet – Litteraturstudie*, SGC-rapport no. 208, Corfitz Nelsson, 2009.
47 *Industriell naturgasteknik*, Styrelsen för teknisk utveckling, ISBN 91-7850-272-1, Stockholm 1988.
48 *Important findings and conclusions in fuel cell system studies conducted during the period 2003-10 – Summary report*, Fredrik A. Silversand, Swedish Defence Materiel Administration (FMV), 2011.
49. *Method and apparatus in catalytic reactions*, Fredrik Ahlström-Silversand EP 0871 543

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