CONSORTIUM MATERIALS TECHNOLOGY for demonstration and development of thermal energy processes

Synthesis of the KME Research Programme

Synthesis Report 2014

Ronny Nilsson, Per-Axel Nilsson, Pamela Henderson

KME-52

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Preface

The project has been performed within the framework the fifth stage of the material technology research programme KME.

KME, Consortium Materials technology for demonstration and development of thermal Energy processes, was established 1997 on the initiative of energy industries and the Swedish Energy Agency. In the consortium, the Swedish Energy Agency, seven industrial companies and 18 energy companies participate. The programme stage has been financed with 60.2% by participating industrial companies and with 39.8% by Swedish Energy Agency. The consortium is managed by Elforsk.

The programme shall contribute to increasing knowledge to forward the development of thermal energy processes for various energy applications through improved expertise, refined methods and new tools. The programme shall through material technology and process technology developments contribute to making electricity production using thermal processes with renewable fuel more effective. This is achieved by

- Forward the industrial development of thermal processes through strengthen collaboration between industry, academy and institutes.
- Build new knowledge and strengthen existing knowledge base at academy and institutes
- Coordinate ongoing activities within academy, institutes and industry

KME's activities are characterised by long term industry relevant research and constitutes an important part of the effort to promote the development of new energy technology with the aim to create an economic, environmentally friendly and sustainable energy system.

Abstract

The KME programme is a base for material technology development for enhanced efficiency, increased fuel flexibility, improved availability and reduced operational costs in thermal energy conversion processes. Focus areas are high temperature corrosion, furnace corrosion and low temperature corrosion in boilers using biomass and waste fuels.

Focus areas for gas turbine have been superalloys with design criteria for thermo-mechanical fatigue (TMF), fuel flexibility and cyclic operation.

For steam turbines focus have been improved blading profiles and coatings. KME program have shown to be an important forum for stakeholders, which have resulted in important contributions in these areas.

Sammanfattning

Forskningsprogrammet KME har inriktning mot att med materialteknisk utveckling som bas höja elverkningsgraden och totala effektiviteten vid användandet av förnybara bränslen i termiska energiomvandlingsprocesser samt att öka tillgänglighet och minska underhållskostnaderna i dessa anläggningar. Programmet inleddes 1997 och dess femte etapp, 2010–2013, har nyligen avslutats. Programvisionen är att bidra till omställningen av energisystemen i Sverige och EU till ett långsiktigt hållbart samhälle och bidra till global miljönytta och internationell konkurrenskraft för svensk industrigenom att utveckla mer effektiva och flexibla termiska energiomvandlingsprocesser med förnybara bränslen och avfallsbränslen. El baserad på förnybara bränslen och avfallsbränslen ska kunna produceras med 3–4% högre verkningsgrad jämfört med dagens gällande nivå för kommersiella anläggningar. Utöver kraven på verkningsgrad, flexibilitet och miljöprestanda har behovet av material anpassade för en mer cyklisk drift ökat betydligt i och med att andelen mer instabil elproduktion i form av vind- och solkraft ökat i många elsystem. De mest betydande problemområdena i samband med energiomvandling med förnybara bränslen och avfallsbränslen är högtemperaturkorrosion i överhettare, korrosion i eldstadstuber och lågtemperaturkorrosion i economiser- och luftförvärmarytor, till följd av förorening med korrosiva ämnen, såsom metallklorider i fast eller smält form.

Resultat av forskningsinsatser inom KME under tidigare programetapper har bidragit till att högre temperaturnivåer kan utnyttjas i överhettare i CFB genom att det avslutande överhettarsteget placeras i sandlåset med betydande minskad risk för högtemperaturkorrosion. Andra viktiga framsteg som kommit till stånd genom forskningsinsatser inom KME för begränsning av högtemperaturkorrosion och därmed högre möjlig ångtemperatur och/eller förlängd livslängd för överhettarmaterial är injektion av svavelbaserade additiv i förbränningsprocessen. KME har även bidragit till utveckling av en ny överhettarkonstruktion för slutöverhettare som används vid förbränning av avfall och RDF. Genom att använda dubbeltuber kan tubväggens yttemperatur ökas över det kritiska ”fönster” där högtemperaturkorrosion uppträder.

De mest betydande resultaten från den senaste programetappen i KME med avseende på **forskning om material för biobränsle- och avfallseldade pannanläggningar vid förhöjd temperatur** avser aluminiumoxidbildande stål, additiv och förbättrade metoder för bestämning av livslängden för pannkomponenter.

Låglegerade stål är olämpliga som överhettarmaterial och som tubmaterial i eldstäder i biobränsle- och avfallseldade anläggningar. Vid medelhöga till höga ångdata krävs mer korrosionsresistenta material. De mest korrosionsresistenta materialen som allmänt används som är höglegerade rostfria stål eller nickellegeringar. Dessa material har utmärkta korrosionsegenskaper, men de är dyra. Forskningsinsatser i KME-programmet har visat att aluminiumoxidbildande (FeCrAl) material också visar goda egenskaper. Dessa material innehåller färre legeringselement och förväntas vara billigare. De blir emellertid försprödade vid driftstemperaturen, men de kan nu användas som spärrskikt (coatings). FeCrAl-stål med lägre innehåll av krom försprödades emellertid inte vid de aktuella temperaturerna och kommer därför att undersökas vidare.

Additiv har visat sig vara ett effektivt sätt att reducera korrosion. Kaolin och rötslam visade sig som de mest lovande additiven för att reducera korrosion i elstaden vid eldning med träavfall. De visade sig också vara de mest lovande vad gäller samtidig minskning av korrosion i eldstadstuber och överhettare. Eftersom kostnaden för avloppsslam är negativ (anläggningarna får betalt för att elda avloppsslam) är avloppsslam som additiv att föredra av ekonomiska orsaker. Additiv med svavelinnehåll visade sig vara effektiva enbart för reduktion av överhettarkorrosion. Alla undersökta additiv kan utnyttjas för att förbättra bränsleflexibiliteten i olika typer av anläggningar.

Ett annat resultat av forskningen inom den senaste programetappen är att långtidstest med sonder (sex veckor eller mer) kan användas för att bedöma livslängden för material i eldstadstuber och överhettare.

De senaste årens forskning avseende **material för tillämpning i gasturbiner** har visat på betydande framsteg beträffande utveckling av superlegeringar och konstruktionskriterier för termomekanisk utmattning (TMF). Forskningen har bidragit med underlag för utvecklingen av ett nytt enkristallmaterial som syftar till att tillmötesgå krav på högre bränsleflexibilitet och cyklisk drift för framtida gasturbiner. Som en följd av den forskning som bedrivits inom KME har Siemens, som en av få turbintillverkare, ersatt konventionella konstruktionskriterier med TMF-kriterier för konstruktioner med temperatur över 600°C.

Termiska spärrskikt (Thermal Barrier Coatings; TBC) används allmänt för att skydda mot oxidation och korrosion vid förhöjda temperaturnivåer. Forskning har även bedrivits för att utveckla metalliska spärrskikt, som har temperaturegenskaper som är överlägsna TBC-skikten, men som knappast tål påkänningar alls. De metalliska spärrskikten kan användas som fristående konstruktionselement eller som delar i ett TBC-skikt. Metalliska spärrskikt med egenskaper som bedöms som lovande har identifierats och två nya material har patenterats under den senaste programetappen.

Resultat från materialforskningen inom KME har visat sig bidra till förbättring av komponenter och processer för både existerande och nya pannanläggningar såväl som ång- och gasturbiner.

Under den senaste programperioden fanns ett särskilt fokus på **process- och anläggningsutveckling** i syfte att undersöka och utvärdera avancerade och högeffektiva koncept för kraftvärmeanläggningar för biobränslen för demonstration i full skala. Arbetet har utförts i nära samarbete mellan tillverkare och energiföretag.

Inriktningen har varit mot att höja ångdata i biobränsle- och avfallseldade kraftverk och kraftvärmeverk, med beaktande av värmebalanser och korrosion och dess påverkan på investeringar, drifts- och underhållskostnader och tillgänglighet.

Konstruktionsstudier för biobränsle (skogsavfall, flis, bark etc) visar att verkningsgradsförbättringar på +2,3%, med en höjning av ångdata till 175 bar, 600°C och med +3,1% för ett alternativ med reheat (175/46 bar, 585/585°C) i jämförelse med konventionella motsvarande anläggningar (140 bar, 540°C) med kapacitet 50–100 MWe. Ytterligare förbättring vid fullast skulle vara möjlig vid temperatur 600/600°C, vilket bedöms kunna vara av intresse för kondensanläggningar.

Utmaningen ökar för en bredare bränsletyp, i det studerade fallet definierat som 75% träavfall och 25% biobränsle. Utöver risken för högtemperaturkorrosion måste korrosionsrisk vid medeltemperatur (huvudsakligen eldstadskorrosion) och lågtemperaturkorrosion beaktas i pannkonstruktionen.

Utvalda koncept (160 bar, 560°C respektive 160/44 bar, 560/560°C) har bedömts som tekniskt genomförbara, men kräver särskilda åtgärder i konstruktionen för att minska korrosionsrisker. Verkningsgradsförbättringen i jämförelse med relevanta riktmärken är i storleksordningen 2,8–3,8%.

Utöver konstruktionsstudierna har riskerna som kan uppstå för en första fullskalig demonstrationsanläggning med avancerade ångdata studerats, för att identifiera betydande risker i demonstrationsfasen. Reservalternativ har definierats i syfte att identifiera en felsäker lösning med högsta ekonomiska genomförbarhet.

KME erbjuder möjligheter till forum där materialtillverkare, system och komponent tillverkare och slutanvändare möts för att diskutera och överväga problem och möjliga lösningar tillsammans med erfarna och kompetenta forskare. KME bidrar härigenom till att skapa enhetlig förståelse av problemområdet och ökar möjligheterna att ta fram nya lösningar.

Den kommande programetappen av KME 2014–2018 är utformad för att fortsätta materialforskningen i syfte att nå en djupare förståelse kring material som kan demonstreras och användas i nya avancerade processer och tillämpningar för energiomvandling samt för att demonstrera och implementera effektivare termiska processer för produktion av värme och el i såväl nya som existerande anläggningar.

Summary

KME is a research programme with material technology development as a base to enhance efficiency in thermal energy conversion processes using climate neutral fuels and waste fuels, as well as to increase availability and reduce maintenance costs. The programme was established in 1997 and its fifth phase, 2010–2013, has recently been completed. The programme has as its vision to contribute to transformation of the energy system in Sweden and the EU into a society which is sustainable in the long term by using materials technology development as a basis as well as ensuring Swedish industry is internationally competitive. The vision is intended to be reached via development of more efficient and flexible thermal energy conversion processes using renewable and waste fuels and enable power production with electrical efficiency 3-4 percentage units higher than presently available technologies. On top of efficiency, flexibility and environmental performance the demand for materials capable of more cyclic operation has been increased substantially due to introduction of high levels of volatile wind and solar power capacity. The main problem areas in energy conversion with renewable and waste fuels are high temperature corrosion in superheaters, furnace waterwall corrosion and low temperature corrosion in economizers and air preheater sections, derived from fouling of corrosive compounds, such as solid or molten metal chlorides. These problems finally lead to reduced availability and increased maintenance and repair costs.

The results of the research efforts in KME during previous programme stages have contributed to higher superheater temperatures for CFB boilers after introducing the final superheater in the loop seal with significantly reduced risk for high temperature corrosion, while also making it possible to increase final superheater temperature. Other key progress made possible by KME research efforts for mitigating high temperature corrosion and increasing steam temperature and/or increasing life time of superheaters is to inject sulphur based additives into the combustion process. KME has contributed in developing a new design for the final superheater when firing waste fuels and RDF. By introducing double tubing the tube surface temperature can be increased above the critical "window" for high temperature corrosion.

The main results from recent KME stages with respect to research on **materials for boilers for biomass and waste fired plants at elevated temperatures** concerns alumina-forming steels, additives and improved methods for estimation of lifetime for boiler components.

As low alloy steels are unsuitable for use as superheater or furnace wall materials in biomass and waste fired plants at medium to high steam data more corrosion resistant materials are needed. The most corrosion resistant materials that are currently widely used in waste fired boilers are highly alloyed stainless steels or nickel base alloys. These have excellent corrosion resistance, but are expensive. In the KME programme it was shown that alumina-forming (FeCrAl) steels also had good performance. These alloys contain less alloying elements and are expected to be cheaper. However, they become embrittled at the service temperature, but they could be used as coatings. FeCrAl steels with lower chromium contents did not become brittle and will be investigated further.

Additives have been found to be an effective way of reducing corrosion. Kaolin and digested sewage sludge were the most promising additives for reducing corrosion in the furnace region of a boiler burning waste wood. They were also the most promising for reducing furnace wall and superheater corrosion at the same time. However as sewage sludge has a negative cost (plants are paid for burning it) this is the additive to be preferred on an economic basis. Sulphur-based additives were effective in reducing superheater corrosion only. All these additives are a means of increasing fuel flexibility.

It was also found that long-term probe testing (6 weeks or more) could be used to estimate the life of components like furnace walls and superheaters.

With regard to research on **materials for gas turbines** the main results from recent year's research are substantial progress with respect to development of superalloys for gas turbines and design criteria for thermo-mechanical fatigue (TMF) which has given useful input to development of a new single crystal material aimed to better fulfil requirements regarding fuel flexibility and cyclic operation in future gas turbines. As one consequence of the research, Siemens has, as one of few turbine manufacturers, replaced conventional design data with TMF data for temperatures above 600^{o}C.

Thermal Barrier Coatings (TBC) are widely used for protection against oxidation and corrosion at elevated temperatures. Research has been performed on metallic coatings, which have superior temperature properties than TBC, but tolerate almost no loads. The metallic coatings can be used alone or as part of TBC. Promising metallic coatings have been identified and two new coatings have been patented during the latest stage of KME.

The KME results of materials research are proven to contribute to improvement of components and processes for both existing and new plants, boilers as well as steam and gas turbines.

With regard to **process and plant development** it was during the latest stages of KME a major goal to study and evaluate advanced and high efficiency concepts for CHP plants, "Reference Power Plants (RPP)", for biomass fuels that could be demonstrated in a full scale plant. The work has been done in co-operation between manufacturers and energy utilities.

The focus has been to increase steam data in biomass and waste fired power and CHP plants, considering design with regards to heat balance and corrosion as well as impact on investment, O&M costs and availability.

Design studies for biomass fuels (forestry residue, wood chips, bark, etc) show an efficiency improvement of +2.3%, with an increase of steam data to 175 bar, 600^{o}C, and +3.1% for a reheat option (175/46 bar, 585/585^{o}C) compared to conventional plants (140 bar, 540^{o}C). These would be feasible for capacities 50-100 MWe. Further full load improvement is of course possible by increasing temperature 600/600°C, which could be of interest for condensing plants.

The number of challenges increases for the wide fuel range, for the studied case defined as 75% waste wood and 25% biomass. In addition to high temperature corrosion risk, among other risks, mid temperature corrosion (mainly furnace corrosion) and cold end corrosion, have to be considered in the boiler design.

Selected concepts (160 bar 560°C and 160/44 bar 560/560 °C) cases have been regarded as technically feasible, but calls for significant measures, in terms of design and mitigation of corrosion risks. The efficiency improvement for main advanced steam data options compared to benchmark is in the range of 2.8-3.8 %.

In addition to the design studies risks that can be present for the first full-scale demonstration plant with advanced steam data have been studied, identifying major risks and challenges in the demonstration phase. Fall-back options have been defined with the prerequisites to identify a fail-safe mode with the uppermost economic feasibility.

KME offers opportunities for a forum where material producers, system and component manufacturers and end users meet to discuss and consider problems and possible solutions together with experienced and competent researchers. KME assists in this sense in creating a unified understanding of problem scenarios and increases the possibility of new solutions.

The coming KME programme stage 2014-2018 is designed to continue materials research for more fundamental knowledge of materials to be applied and demonstrated in new advanced processes and applications for energy conversion and to demonstrate and implement more effective thermal processes for electricity and heat production in both existing and new plants.

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1 Introduction

1.1 Background

KME is a research programme with material technology development as a base to enhance efficiency in thermal energy conversion processes using climate neutral fuels and waste fuels. The aim hereby includes improvement of utilization both limited fuel sources and heat sinks for CHP plants with high fuel flexibility as well as to reduce environmental impact. The programme is financed by the Swedish Energy Agency together with a consortium of interested parties, energy utilities and manufacturing industries within the energy sector, as well as material manufacturing industries.

The motive for the research efforts is that renewable and waste fuels contain several critical compounds, (K, Na, Cl, Pb) that have caused large problems, such as high temperature corrosion, furnace corrosion and low temperature corrosion. These problems have been causing significant unavailability and maintenance costs in existing plants as well as a reducing the possibility to utilize the efficiency potential in thermal steam processes, defined by state of the art fossil fired power plants.

The KME stage 2010-2013 is the fifth phase of the programme that was established in 1997.The programme has during the last phase been divided into two main focus areas; Material technology base programme (MATBAS) and "More Effective Power Production" (EPP), with the focus to study and demonstrate improved processes.

1.2 Targets for the Programme

KME is a consortium with material technology development as a base to enhance efficiency in thermal energy conversion processes using climate neutral fuels and waste fuels. The aim hereby includes improvement of utilization of both limited fuel sources and heat sinks for CHP plants with high fuel flexibility as well as to reduce environmental impact from energy conversion.

The programme will contribute to the conversion to a sustainable energy system by development of more effective energy processes in problem oriented research projects. Competence Centre for High Temperature Corrosion (HTC) at Chalmers carries out research to establish fundamental understanding of corrosion mechanisms. HTC is a knowledge base for KME and contributes actively to KME as a programme partner.

The long-term vision of the programme includes support to an erection of a new full scale demonstration CHP plant, fired with renewable bio fuels and refuse fractions, with at least 3-4% (percentage points) higher electrical efficiency, compared with commercial plants that have been built today.

Targets for gas turbine development in KME include increasing efficiency, improving operation flexibility, improving lifetime for hot gas parts and decreasing operation and maintenance costs. Improving the capability of using renewable gaseous and liquid fuels are of large interest.

1.3 Objective

The objective with this synthesis report is to in a holistic perspective summarize and discuss the results of the KME programme projects at the end of the fifth programme stage in 2014, interconnections between projects, drivers, challenges and how the findings could be implemented in existing and new power and CHP plants.

1.4 KME Programme 2010-2013 in brief

The activities within KME research programme have since the start in 1997 been marked by continuity between the different programme stages, i.e. it has usually been the case that projects have been completed and advanced or deepened in successive stages of the programme.

During the fifth programme stage 2010-2013, 21 research projects were carried out. The projects were, as in previous stages, conducted through cooperation between one or more industrial parties and a university or research institute acting as the performer. This latest programme stage was divided in two research areas – The Materials Technology Base Programme and the Programme area More Effective Power Production from Renewable Fuels (EPP). The EPP research area can be seen as a concentrated effort on demonstration of the results from previous KME and HTC programmes and at the same time identify the needs for further research within both material and process technology, in order to be able to demonstrate considerably higher electrical efficiency in combined heat and power plants using renewable fuels. All projects performed in the fifth programme stage are listed in Annex 1.

The starting point shared by both areas is the fact that materials technology process development should help to ensure that renewable fuels and waste can be used efficiently in order to produce electricity and heat within thermal energy processes.

2 Driving forces for R&D and demonstration

2.1 Market development and requirements

The KME programme has as its vision to contribute to the transformation of the energy system in Sweden and EU into a society which is sustainable in the long term by using materials technology development as a basis as well as ensuring Swedish industry is internationally competitive. The vision is intended to be reached via development of more efficient and flexible thermal energy conversion processes using renewable and waste fuels and enable power production from these fuel sources with electrical efficiency 3-4 percentage units higher than presently available technologies.

The requirements for the R&D and demonstration efforts are in many respects set by the market requirements, which in turn are reflected in market prices for power and heat but also by legislation and incentives controlled by political will. The effects on the technical development can be seen in several different ways. An example is the introduction of high levels of volatile wind and solar power capacity that is developing a market for fast start and ramping power production with a demand for materials capable of much more cyclic operation than just a few years ago. On top of fuel flexibility, operational flexibility and environmental performance the market will still require highly efficient and reliable plants for heat and power production.

2.1.1 Condensing Steam Turbine processes and plants

Boilers

Increasing plant efficiency is an effective way for reducing CO2 emissions and saving natural resources at the same time.

State of the art for pulverized coal-fired power plants now being built in Europe, has a capacity of 800 MWe and "Ultra Supercritical" steam data; an advanced “once-through” boiler, corresponding to 280 bar/600/620°C with a net electrical efficiency of 46%. The potential with this steam data is expected to be 47% with hard coal and 44% with lignite in 2020.

International R&D, has a focus on materials development to further enhance the steam temperatures to about 700°C, using nickel based alloys. This would mean a potential electrical efficiency of about 50% with coal as the fuel. In contrast, the average efficiency of plants in the EU is just 36%. The European research in this area started with the material development program AD 700 (Advanced 700 °C Power Plant Project), further developed with COMTES700 (Component Test Facility for a 700 °C Power Plant; completed in 2012) and continued with COMTES+ with more material testing, particulary thick-walled components, manufacturing and repair concepts. COMTES+, comprises the German HWTII project and the European ENCIO project. HWTII started in 2011 and will run until 2014. The aims of HWTII are manufacturing and qualification of thick-walled components from nickel-base alloys and testing of the components at steam temperatures up to 725°C under defined cyclic conditions. ENCIO started in 2011 and was due to run until 2017, but will finish prematurely in 2014. The objective of the ENCIO project was to solve the remaining scientific and technical problems to allow the commercial use of 700°C technology.

Improving the energy efficiency of coal-fired power plants is considered to open up opportunities for carbon capture and storage technologies.

In order to reduce CO2 emissions and rapidly increase the renewable share of power production, wood pellets are introduced or planned to be co-fired with coal or natural gas in large condensing plants in several countries. However, in recent years there are also plans for mid-size biomass fuelled condensing-extraction plants, up to 300 MWe, for wood pellets and wood chips (for example in UK and Belgium).

Steam Turbines

The development for steam turbines today is primarily focused on very large coal-fired power plants (in terms of temperature and pressure) with Ultra Supercritical steam data (temperatures up to 620°C) and to some extent, nuclear power plants (for improved efficiency).

According to Siemens the development of new turbine materials and optimized power plant components and processes are directed to achieve the efficiency targets of more than 50% in the case of lignite steam power plants and 53% in case of hard coal steam power plants by the year 2020.

Research and development is currently focusing on new nickel-based alloys designed to withstand steam parameters of 700°C/720°C and 350bar and achieve efficiency values up to 50%. By minimizing pressure losses, own consumption and condenser pressure, as well as using multiple preheating cycles, efficiency of the plant could increase to even more than 50%.

International R&D programs between operators and suppliers have been established, where the EU programme COMTES700 is one example.

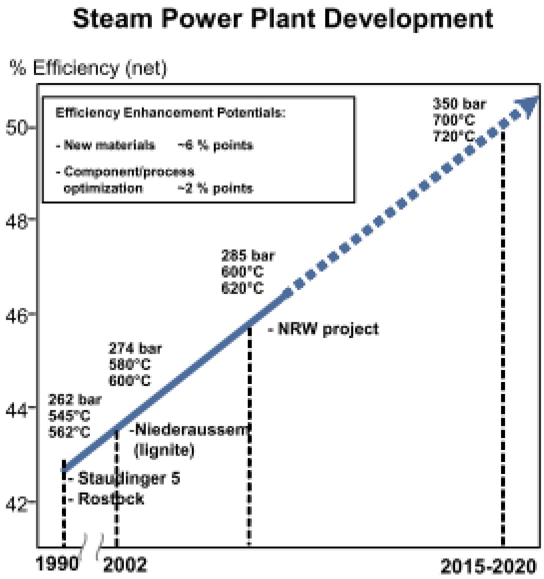

Figure 2.1 Efficiency in steam turbine power plants according to Siemens

2.1.2 Combined Heat and Power (CHP) plants

Boilers for Virgin Biomass fuels

For virgin fuels common steam data for mid-size plants built in Sweden in the last 10-15 years is 140 bar, 540ºC, even if the more advanced configurations (reheat) and steam data have been available. For larger plants higher steam data up to 160 bar and 560ºC can be offered today. One example is the Fortum Värtan plant to be commissioned 2016 in Stockholm with a boiler capacity of 330 MW_{th} and steam data of 140 bar and 560°C.

The limiting factor for steam temperature is for virgin biomass mainly the risk for high temperature corrosion caused by chlorine and alkaline compounds in the fuel. It has been found that the higher content of alkali metals and the lower content of sulphur in combination with chloride in renewable fuels play a major role in the corrosion process. Condensation of alkali chlorides on the superheater tubes is the major cause of the corrosion. In order to reduce high temperature corrosion risk the use of different kind of sulphur additives is, in combination with appropriate material choices, a well proven and commercial method for conventional steam data.

Higher superheater temperatures have been made possible for CFB boilers after introducing the final superheater in the loop seal, a design which has been developed with contributions from KME, with significantly reduced risks for high temperature corrosion. Corrosion testing in the earlier stages of KME has confirmed the lower corrosion rate with the final superheater in the loop seal.

Boilers for Waste wood and waste derived fuels

The challenges when using fuels such as waste wood (demolition wood) or Refused Derived Fuels (RDF) are increasing. In addition to an increased high temperature corrosion risk at the superheaters these fuels contain a high content of metals like Pb and Zn, forming metal chlorides that together with fouling and rapidly fluctuating combustion conditions causes furnace corrosion (mid-temperature corrosion) and low temperature corrosion in economisers and air preheating sections.

In order to reduce the furnace corrosion, due to both uneven combustion conditions and critical compounds, the furnace steam pressure and thereby the furnace wall temperature is reduced, compared to virgin fuels. Protection of critical parts, for example with metal spraying or cladding (welding) with Inconel 625 (Ni-base alloy) in addition to refractory is today commercial measures.

Steam pressure for commercial plants for waste wood and smaller admixtures of RDF is 80-100 bar. Design steam temperatures are very much depending on the technology, typically 480-500^{o}C for BFB boilers and 500-540^{o}C for the CFB technology.

Steam Turbines
For steam turbines used for CHP the differences compared to condensing plants are generally the size but for new plants also the fuel. Technically, it is possible (within certain limits), to utilise enhanced steam data for CHP, although the possibility to use high pressures is very much dependent on the plant size and especially the volume flow and boundary losses in the turbine.

For biomass and waste fuel plants it is not primarily the steam turbine technology that limits the steam data and hence efficiency, but permissible temperatures in boiler superheaters, evaporators and other heat transfer parts.

For a typical CHP steam turbine capacity of 25-100 MWe there are, according to Siemens, steam turbine sets available up to about 170 bar 570^{o}C. What is available from other suppliers varies and is depending on size, although at least 140 bar and 540^{o}C would be available from several suppliers.

2.1.3 Gas Turbines

The gas turbine market can be divided broadly in gas turbines for larger and larger combined cycle power plants, where the exhaust gas from the gas turbine is utilised in a steam turbine, and in gas turbines units for stand-alone operation as peak load or regulating power plants. On certain markets gas turbine units with exhaust gas boilers for base load operation are demanded. A general trend is a growing demand for distributed power, i.e. placing smaller units for power supply (less than 50 MW) closer to the end user, rather than a few giant power plants.

Large combined cycle power plants are predominantly fuelled with natural gas and the main research target is to improve efficiency by higher gas turbine temperatures. The gas turbine efficiency in large combined cycle power plants has improved more or less linearly from about 32% in the beginning of the 1970s to the current level, which is approximately 60% (net) for the most recently built large plants. Much of this development is due to more efficient gas turbines with higher turbine inlet temperatures. Today, the temperature is about 1500°C and aiming to reach 1700^{o}C, which would provide efficiencies for the largest plants of 65% and upward in 2030.

For smaller plants there is a more explicit demand for adaption of gas turbines towards renewable fuels, such as syngas from biomass, biogas from waste or biodiesel. The conversion to renewable fuels put demands on the development of combustion technology since these fuels have different energy content and combustion characteristics. During later years also the conditions for operation of peak load and regulating power plants have been changed and an increased demand for units capable to a more cyclic operation has been observed. Cyclic operation in this context means an increased demand for starts and stops of the plants, or at least of varying the pressures and temperatures in cycles, to an extent that only a few years ago seemed inconceivable. The most significant driver for this development is the increased need of regulating power due to the vast expansion of electricity generation from sources that are dependent on specific weather conditions to be able to make a contribution to electricity generation in the power system, such as solar and wind power. This development is in general visible in the whole of the European continent including Denmark.

2.2 Driving forces and barriers

2.2.1 General

One of the main driving forces for developing high efficient power and CHP plants is of course the market which mainly is set by the electricity price development, but to a great extent also the support systems such as green certificates, feed-in tariffs and other mechanisms for renewable energy and efficient technologies.

The incentives are mainly controlled by national and EU political goals and strategies. In order to give these a real impact on both technology development and to initiate new demonstration as well as commercial plants, it important that these are predictable during a major part of the economic life time.

2.2.2 Boilers

The introduction of taxes in Sweden, in 1991, on fossil fuels used for heat production, especially an successively escalating carbon tax, generated fuel conversions and modification of existing plants as well as investment in new plants. The following problems and insights regarding high temperature and furnace corrosion have been a driver for developing new designs, combustion control and material development.

The green certificate support system for renewable power in Sweden (Elcertifikatsystemet) that was introduced in 2003, have had a huge impact on the market for biomass CHP boilers. The direct driver for high steam data is dependent on the relation between electricity prices, in combination with the supports system, and the fuel cost.

Support systems for renewable power generation and efficient power and CHP, as well as commitments to increase the share of renewable energy vary within EU countries.

The underlying driving force for political incentives is of course to support maximum renewable electricity from limited fuel sources and heat sinks like district heating systems and steam consumers. Directive 2012/27/EU on energy efficiency promotes high efficiency cogeneration.

A continuing driver is the plant owners' search for cheaper fuels such as waste wood, RDF, sludge, stumps, etc. This is of course mainly to improve profitability, but other important reasons are the competition from other heating options in areas where district heating systems are established and future reduced heat demand in new as well as in existing buildings.

These cheaper fuels contain amounts of critical compounds and substances leading to a higher risk for corrosion, erosion and increased wear.

2.2.3 Steam Turbines

Steam turbines for enhanced steam data are mainly developed for large fossil based power plants. These techniques can in principle also be used in smaller steam turbine systems if the developer sees a future market for the actual capacity range. A challenge is to make these smaller scale systems, comprising advanced design, high steam data and reheat, economically competitive. Further challenges are to reach high efficiency turbines for smaller capacities, considering physically limitations such as border and blade end losses as well as other design aspects. Even with high speed HP turbines (up to 12000 rpm) there will be limits for the pressure for small units, in order to achieve a realistic blade length.

Technical challenges are steam side corrosion. Another challenge is to handle high steam pressure in small steam turbines, keeping boundary losses within levels that are economically viable.

Steam turbines for thermal solar power plants up to 50 MW (380°C and 100 bar) have been built in USA and in Spain. The intermittent operation with many starts/stops requires steam turbines with good fatigue strength, rather than high efficiency. The Siemens steam turbine SST 700 was during a period of time market leader for this distributed power segment with almost 100% of the market. These kinds of plants utilising solar power are increasing both in number and capacity but are, however, still in need of public or green mechanism support.

The main driver for smaller steam turbines is today cost optimization and price, rather than efficiency. Scale factors make smaller CHP plants more expensive in specific terms and less competitive compared to heat only plants, with the same fuel.

2.2.4 Gas Turbines

The competitive edge within gas turbine development is generally supposed to be gained through high efficiency, guaranteed long term operational reliability and low emissions.

At the same time gas turbines are subject to more corrosive environments, due to a development towards renewable fuels. An important goal for the gas turbine industry is reduction of emissions as well as continued development towards greater operational and power production efficiency.

From a materials perspective the greatest challenge concerns fuels that emit corrosive combustion products. Corrosion of gas turbine materials is studied within the framework of the Competence Centre for High Temperature Corrosion (HTC). For the continued development of competitive gas turbines it is essential to improve materials and surface coatings for high temperatures, corrosive environments and longer service life.

The demand for more cyclic operation due to increased demand for regulating power puts higher requirements on gas turbine materials. Traditionally the main design challenges on gas turbine components have been related to creep resistance but a more cyclic operation leads to higher requirements on the thermo-mechanical fatigue (TMF) properties of the materials. Consequently, the importance of TMF properties has increased in design and in selection of materials for gas turbines.

3 KME results to date

3.1 Introduction

The unifying idea behind the KME programme is that materials technology development should help to ensure that renewable fuels and waste can be used more efficiently in order to produce electricity and heat within thermal energy conversion processes. The programme focuses on the development of materials technology and the development of process and plant technology with the aim of contributing to the construction of a demonstration plant with 3-4 percentage units higher electrical efficiency than commercially available today.

In the following sections the most relevant results from recent KME programme stages are presented. The chapters 3.2–3.3 cover the material developments in brief, whilst chapter 3.4 is intended to summarise the results from process and plant technology research.

3.2 Boilers for biomass and waste fuels

Work with developing materials for biomass and waste fuels has been focused on reducing corrosion to allow higher steam temperatures (higher electrical efficiency) to be achieved or to increase the fuel flexibility to allow cheaper and more corrosive fuels to be used. A wide range of materials has been tested. Alumina forming alloys, which form a protective layer of alumina, have emerged as a new type of alloy (for use in boilers) because they have excellent corrosion resistance.

Fuel additives were also found to be an effective way of reducing corrosion and it appeared that additives to reduce corrosion continue to have an effect even after the additive is removed, i.e. when the fuel chemistry is changed to a more corrosive fuel. This is called the “memory effect”.

A wide range of materials have been tested and compared. As expected austenitic stainless steels and nickel-base alloys that form a protective chromia layer also showed good corrosion resistance, but low alloyed steels did not perform well, even if the temperature of the metal was reduced.

Most boiler testing was performed with probes. Parallel testing of superheater and waterwall tubes and probes under the same conditions showed that the results from probe testing were reliable enough to be used for predicting lifetimes if the corrosion rate was linear.

3.2.1 Alumina formers to improve corrosion resistance

One of the main results to come out of the programme is the use of alumina forming alloys (FeCrAl alloys or “Kanthal” type materials) as alternatives to austenitic stainless steels (FeNiCr alloys) or even conventional nickel base alloys. While these alloys have not yet been approved for pressure vessel applications, like superheaters or furnace walls, they can be applied as coatings.

Corrosion in biomass and waste fired boilers occurs at relatively low metal temperatures (400-600°C) in a chemically aggressive environment. The materials conventionally used in these environments like stainless steels owe their good corrosion resistance to the formation of chromium oxide (chromia) which is protective. However the chromia is attacked by alkali salts to form alkali chromate (e.g. K2CrO4) which is non-protective. This reaction depletes the protective oxide of chromium and forms a poorly protecting chromium-iron oxide resulting in a sudden increase in the corrosion rate (so-called breakaway corrosion).

A possible strategy to avoid this problem is to use a completely different type of material that forms protective oxide films not attacked by alkali at the temperature range of interest, for example alumina-forming alloys such as FeCrAl steels. The usefulness of these materials is based on a slow growing and highly protective layer on the material surface. These steels are traditionally used for heat-treatment furnace components at much higher temperatures of 800-1100 °C, and were previously not considered for use in the temperature range 400-600 °C mainly due to the slow diffusion of aluminum in the alloy at these temperatures.

The corrosion properties of FeCrAl alloys were examined in several projects from several aspects.[1]

The results showed that the corrosion resistance of certain components of biomass and waste-fired boilers, such as thermocouple shielding tubes, superheater coatings or shielding and coatings for furnace walls can be improved significantly if the existing material is replaced with iron-based alumina-forming materials. The alumina-forming material performed as well as commonly used Ni-base alloys and much better than stainless steels. A surprising result was that the commercial pre-oxidation treatment is not favourable when the material is used at temperatures below 700°C. This means that production of major boiler components in alumina-forming material would be greatly facilitated.

3.2.2 Additives to reduce corrosion

Additives to reduce corrosion have been studied in several projects.[2]. One strategy to avoid corrosion problems is to change the atmosphere in the boiler, e.g. by changing the fuel chemistry. It has been proven that deposit formation and superheater corrosion can be counteracted by co-combustion with sulphur-rich fuels or additives. Digested sewage sludge often contains high amounts of phosphates and sulphates (depending on the treatment process). Phosphates are believed to have a similar effect on the gas phase reactions as sulphates.

[1] KME 507, KME 508, KME 512 and KME 519 – KME 507 and KME 519, run by HTC at Chalmers University, were closely connected. KME 507 looked at FeCrAl alloys in waste and waste-wood fired plant and KME 519 looked at the corrosion of FeCrAl alloys when sulphur was added to the fuel.

[2] KME 504, KME 508, KME 512, and KME 519

Pilot scale exposures showed that by increasing the dosage of both sulphur and phosphorus containing additives the alkali chloride content in the flue gas could be decreased. In the flue gas phosphorus-containing additives had the best effect compared to the sulphur-containing additives. However, for reducing the chloride content in the deposits the sulphur-containing additives were most effective.

It was also shown in full scale plant testing that ammonium sulphate reduced corrosion even at a steam temperature of 600°C when burning difficult fuels like recycled wood.

Another project[3] was entirely about additives and the goal was to find additives suitable to reduce both furnace wall *and* superheater corrosion. Additives are not commonly used specifically for reduction of waterwall corrosion. Usually, when additives are fed into the boiler together with the fuel or with the bed material in FB boilers, the target is to reduce fouling and/or the defluidisation risk. Based on previous research[3] additives were initially considered and five additives with the greatest potential were selected for testing. They were sulphur, digested sewage sludge, kaolin, foundry sand and lime.

Sulphur was selected as a reference, since there is much experience from using this additive already. It is known to have a positive effect on superheater corrosion and there was a hope that it might also be beneficial when it comes to waterwall corrosion.

Digested sewage sludge was selected as this is a cheap additive (or actually the plant is paid for receiving it) and has been shown to reduce bed agglomeration, deposit formation, and superheater corrosion in fluidised bed boilers.

Kaolin and foundry sand were selected as they were expected to cause a substantial reduction in alkali in the deposits and flue gases in the furnace, and possible also a reduction of heavy metals. Foundry sand was selected as a possible cheaper alternative to kaolin.

Of the five different additives considered to decrease the risks (deposits, fouling, and corrosion) in the combustion chamber in a boiler, two were identified as the most favourable – sewage sludge and kaolin. Limestone increases the risk for chlorine deposition and corrosion, while foundry sand also contains other elements e.g. potassium, which may be risky. It was also found that the lead content of the waste wood affected the corrosion – a higher lead content gave rise to more corrosion. This is an important result because the lead content of waste wood varies greatly depending on the source.

The corrosion memory effect, which involves fuel changes – and therefore additives - has been studied in a separate project.[4] Tests were performed in two boilers in the same plant that run on different fuel mixtures and experience very different corrosion attacks.[5]. One was a boiler experiencing high corrosion and the other with medium corrosion. Metal and flue gas

[3] KME 512
[4] KME 608
[5] E.ON´s plant in Händelö, Norrköping; P13 and P14

temperatures at exposure points were kept as similar as possible, the aim being to find the effect of the fuel and switching between different fuels, on the corrosion rate of a probe.

The probe was then shifted between the two boilers in sequence and it was shown that pre-exposure in a medium corrosion environment reduced the corrosion when the sample was exposed in a high corrosion environment, i.e there existed a corrosion memory effect. In this test the corrosion rate was reduced from approximately 30 times higher to approximately seven times higher when exposed first in the boiler with the lower corrosion rate.

3.2.3 Comparison of Materials

The low alloy steel 16Mo3 is commonly used as a furnace wall material. The variation of corrosion rate with temperature was investigated for this steel, by using a probe with a temperature gradient.[6] The fuel was waste wood. Increasing the steam parameters from 140 bar/540°C to 190 bar/600°C/600°C means that the water temperature in the boiler will increase by 25°C. The results given in Figure 3.1 show that the corrosion rate increases steeply with temperature at temperatures above about 390°C, which is today's wall temperature. Reducing the pressure to 90 bar, gives a water boiling temperature of about 310°C and a corresponding metal temperature of 360°C and reduces the corrosion rate of 16Mo3 by 20-30% from today's level. A final pressure of 26 bar (boiler pressure 31 bar) is needed to reduce the wall temperature to 285°C (water temperature 235°C).

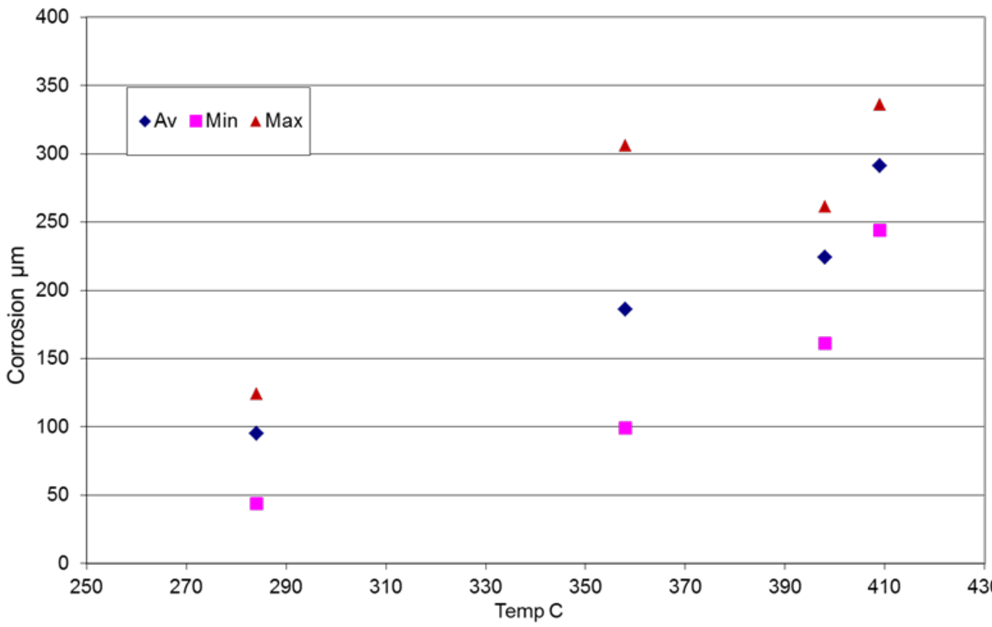

Figure 3.1 Variation of furnace wall corrosion rate in µm per 1000 h with metal temperature in °C for the commonly used low alloy steel 16Mo3. The average, maximum and minimum of 20 measuring points are shown. Fuel is waste wood.

[6] KME 508

It is clear then that the alloy 16Mo3 is not suitable as a furnace wall material at pressures of 90 bar and above when burning waste wood, so other materials, as coatings were considered. The nickel base alloy (Alloy 625) drastically reduced the corrosion rate as did a FeCrAl steel. Austenitic stainless steels showed moderate corrosion rates and could be an alternative to Ni-base alloys for protecting furnace walls. A comparison of materials is given in Figure 3.2.

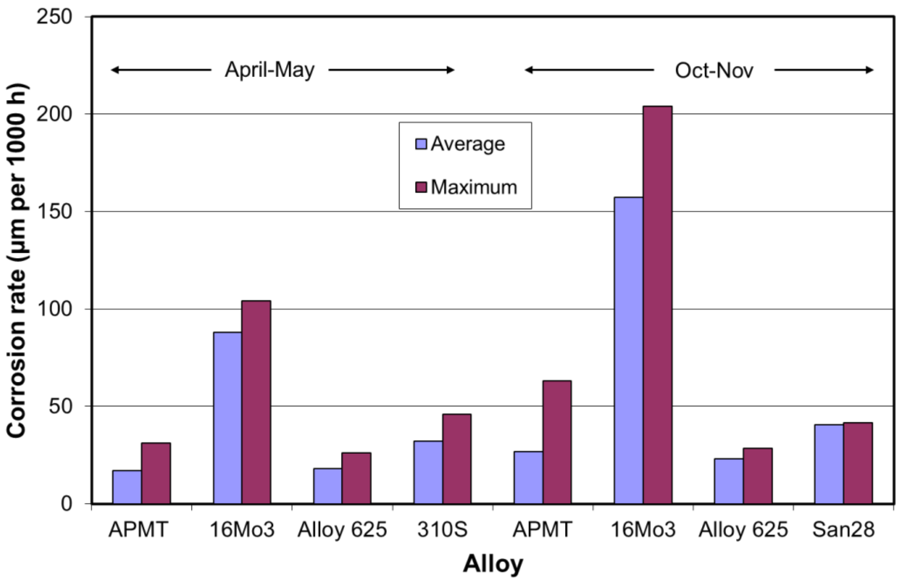

Figure 3.2 Average and maximum corrosion rates for probes exposed April-May 2012 and October-November 2012 in the furnace wall of a boiler burning waste wood. Metal temperature 400°C. APMT is a FeCrAl steel, 16Mo3 low alloy, Alloy 625 Ni-base and 310S and San28 are stainless steels.

In Figure 3.2 it can be seen that higher corrosion rates were measured during testing in October–November than in April-May, for the same materials. This was attributed to the higher boiler load during the autumn.

Some coated test panels were welded into the walls of the furnace and evaluated after a number of years. The method of applying the coating was found to be important. Some thermally sprayed coatings adhered very well, but not all. In general, the thermally sprayed coatings did not adhere as well as the weld overlay coatings.

As regards metal loss (corrosion), the nickel-based alloys (welded or thermally sprayed) showed negligible loss (too small to be measured accurately) and the stainless steel showed a loss of 35-90 µm per year (less than 0.1 mm), also very small. The 16Mo3 reference sample showed a loss of about 0.6 mm per year.

3.2.4 Estimation of corrosion lifetime from probe tests

Corrosion probe exposures in boilers are commonly used to estimate the lifetime of boiler parts. But how well do probe tests estimate the corrosion rate of the actual boiler parts? This question was answered in several projects in the latest stage of KME.[7]

The results showed that corrosion rates of the probe exposed samples, simulating boiler components, were generally consistent with the corrosion rates measured on the actual components.

It was also shown that the start up of the corrosion probes seemed to be of great importance for the overall corrosion rate (especially for shorter exposure times). The results indicated that a start up with cold probes directly into a hot boiler increased the corrosion attack. Hence, probe exposures are a possible way of investigating the potential corrosion rate of superheaters and furnace walls. However, it is important to stress that the probe exposures need to, as far as possible, mimic the thermal and environmental history of the superheater or furnace wall.

3.3 Steam Turbines

In addition to the efforts to increase efficiency by enhanced steam data there is still a potential for reducing losses in the steam turbine. A project[8] that has been conducted in collaboration between the department of Energy Sciences at Lund University and Siemens Industrial Turbomachinery in Finspång, has studied the potential by introduction of the advanced blading for industrial size steam turbines.

The reason why a larger turbine performs better than a smaller one can be explained by the relative importance of clearance and secondary flows. The blading aerodynamics are the local flow processes in each stage in the turbine. The efficiency of a turbine stage (i.e. a stator and a rotor) is limited by losses due to e.g. dissipation in boundary layers, dissipating of secondary flows, leakage mixing and lost work, etc.

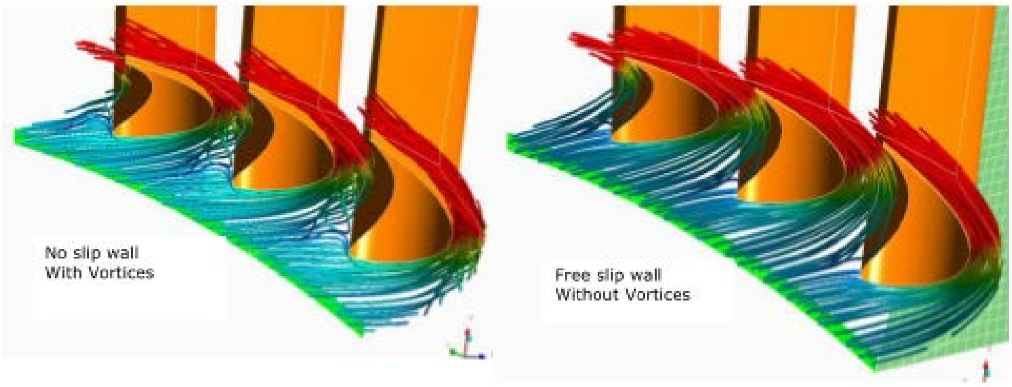

Figure 4.5 Secondary Flow

Figure 3.3 Seconday flow

[7] KME 508, KME 509 and KME 514
[8] KME 607

The goal of the project can be summarized as “exploring the future flow path for higher-performing steam turbine plants” by evaluating the maximum cost effective efficiency potential of industrial steam turbines. The latter is by utilizing improved blade profiles and advance stacking technologies.

The work has been carried out in state-of-the-art turbine design tools and comprises: one-dimensional tool, two-dimensional throughflow analysis and full three-dimensional high-fidelity CFD. The latter was not part of the initial plan but was introduced because it was necessary to establish a baseline for back-to-back comparisons. The datum stage is a tall stage in an assumed Siemens SST-900 turbine.

The work, however, is generic for low-reaction steam turbines. The work shows that the stage performance can be increased. The full potential, however, is still to be evaluated as the work in the project continues. The project work at Lund University effectively started in late 2012 and is not yet completed.

3.4 Gas Turbines

The research efforts on gas turbine development within KME is directed towards different aspects of improvement of materials to contribute to improved efficiency and also fulfilling demands on fuel flexibility and cyclic operation in future gas turbines.

The KME projects in gas turbine research are generally performed as collaboration projects between industry and research centres. There is a strong continuous collaboration between Siemens Industrial Turbomachinery AB and Linköping University, but also between Siemens and other research centres and material manufacturers in the frame of KME.

The problems to be solved are mainly caused by improving the efficiency by use of elevated temperatures, while taking into account the changing operation conditions caused by more cyclic operation, often in more corrosive environments.

Efforts performed in previous stages of KME have contributed to improvement of materials, for example 9-12%Cr materials, resulting in several new more corrosion-resistant materials for use at elevated temperatures, which are now integrated in the design of Siemens’ supercritical steam turbine for 620^{o}C steam data. It has been shown that these materials also can be used to contribute to improvement of the performance of gas turbines, specifically in the compressor stage. The KME projects have hereby contributed to bridge knowledge and experience between steam and gas turbines.

Other efforts have included testing and validation of combustor materials in reducing environments, critical for increased fuel flexibility when renewable fuels are introduced. These research efforts have contributed largely to the design of the so-called fourth generation Dry Low Emission (DLE) burners with NO_x levels below 10 ppm, which are now part of numerous Siemens’ products.

Another example of efforts from earlier stages of the KME program resulting in improved competitiveness for the participating gas turbine industry is projects concerning processing and residual stresses in super-alloy materials, specifically Inconel 718, which have contributed to cost savings improving the competitiveness, for example, of Siemens' gas turbine SGT-800.

During the recently completed KME stage research projects have been directed towards further improvement of materials that to a great extent set the limits for the efficiency of modern gas turbines and towards durable coatings for use as protective overlays and bondcoats. Among materials both superalloys and composites are studied.

3.4.1 Development of superalloys and TMF design criteria

The research on nickel-base superalloys started during the previous stage of KME, with the aim to achieve better understanding of the metallurgical mechanisms of deformation, damage and degradation of cast nickel-base superalloys used in manufacturing of gas turbine blades. Initially[9] the research was focused on tests and thermo-mechanical fatigue modelling of nickel-base materials to be installed in the gas turbine's most temperature exposed parts. Typically, creep resistance is the most important parameter in the selection of material for these high temperature exposed parts. However, demands on more cyclic operation increases the importance of thermo-mechanical fatigue (TMF) as a significant factor affecting the design of the gas turbine's theoretical lifespan. Many of these parts necessarily contain fractures, which easily initiate cracks, in the form of depressions or holes that involves tension and stress concentrations, which further increases the complexity of the evaluation of the theoretical life expectancy with respect to fatigue phenomena.

The further research[10] was more focused on component-near conditions of multi-axial stress states at notches, environmental impact (oxidation) on fatigue and aspects of life time assessments of long term exposed material, aiming to validate the use of single crystal materials in industrial gas turbines. The research has given useful input to the development of the new single crystal material STAL15, an alloy which is aimed to better fulfil the requirements regarding fuel flexibility and cyclic operation in future gas turbines and is oxidation resistance with a chromium content of 15%. The motive for development of STAL15 is to develop a more corrosion-resistant alloy, enabling operation with renewable fuels, and the KME project has contributed to evaluate the thermo-mechanical properties of the new alloy, which now during 2014 is introduced in the production of turbines.

These sequential projects are considered as a good example of successful research, from the initialisation with tests and modelling during one KME phase to validation during the subsequent KME phase to then be used in practical operation. The results from the KME projects have also meant that Siemens, as one of few turbine manufacturers, has largely replaced conventional design data with TMF data for temperatures above 600^{o}C.

[9] KME 403 and KME 410 performed during the prevoius programme stage (2006-2009)
[10] KME 502

3.4.2 Durable coatings for high temperature and corrosive environments

KME projects on metallic coatings MCrAlX (M: Ni or Co; X: alloying elements of minor addition) for oxidation and corrosion protection of superalloys have been an important part of the on-going process of introducing coatings on more and more products. The metallic coatings can be used alone as overlays or as bond coats in Thermal Barrier Coatings (TBC). The metallic coatings have superior temperature properties but tolerate almost no loads at all.

In the most recent project[11] new coatings have been developed for use in the hottest parts of the gas turbine, which is a prerequisite for building gas turbines with high combustion temperatures and thus low emissions and high efficiency.

The aim of the project was to develop new durable MCrAlX materials optimised for the operation conditions in land based gas turbines of medium size (10-60 MW). Such gas turbines are used for both base load (long loading duration at high temperatures and few cycles) and peak load (frequent cycles) operations; thus it is important that the coating can resist both long term oxidation and thermal cycling. The mechanisms of coating degradation during exposure to high temperature and thermal cycling and the influence of the coating composition are investigated by experiment and simulation. Mechanical properties are also characterized by adhesion tests and hardness measurements.

One nickel based and one chromium based MCrAlX with promising performance have been identified and patented.

3.4.3 Composite for hot corrosion and elevated temperature components

$MoSi_2$-based composite is one of the candidates to replace conventional materials in gas turbines, due to its higher temperature capability and superior oxidation resistance compared to superalloys. It was made evident during the previous KME stage that a composite ($(Mo_{0.9}Cr_{0.1})Si_2$ +15vol% ZrO_2) has a high oxidation resistance at 1400 °C and remarkable sinterability. A ceramic manufacturing method, based on pressure-less sintering (PLS), was developed to produce a prototype of a heat shield for the SGT-800B turbine.

Further research during the recently completed KME stage[12] was aimed at evaluation of mechanical and thermal cycle fatigue properties of the chromium-alloyed composite compared with commercial candidate materials.

It was concluded that a specific composite ($MoSi_2$+15 vol% ZrO_2) possesses excellent intrinsic oxidation resistance up to 1500°C and thermal cyclic oxidation resistance up to 1300 °C. The bulk of this composite is suitable for high temperature components used at cyclic oxidation conditions, but the detrimental Si-depleted silicide formed at the surface has to be avoided. The possible solution could be adjustment of oxygen content in the sintering gas, and applying a suitable pre-oxidation post sintering treatment. According to

[11] KME 503
[12] KME 505

the results, it is advisable to focus the activity on lowering the chromium addition in the MoSi2 matrix, and tailoring the sintered surface of the composite. The achieved technique can be applied to the development of related MoSi2 based materials produced by PLS technique.

This is an example of a project with a ”high risk factor” where KME's involvement is more or less necessary for Siemens to be able to participate in more prospective future projects.

3.4.4 Weldability for high temperature applications

When superalloys are more and more frequently used in today’s gas turbines, the requirements on welding repairs of such materials become inevitable. As superalloys are classed as difficult to weld, it is important to master a basic understanding of how these materials and welding methods should be combined.

A project[13] with the aim of finding specific combinations of alloys, welding techniques and appropriate heat treatment to increase the potential for applications in gas turbines was performed during the KME stage 2006-2009. Tests and physical-metallurgical modelling gave good results which are useful in materials development and the execution of repair welding of components.

In the current KME period the research[14] has been directed towards developing a testing rationale that can be used to assess the overall weldability in a reliable way and to choose a reliable testing method (the Varestraint method) to assess susceptibility towards hot cracking and strain age cracking.

This is an example of projects where experience from the aerospace industry is made available for stationary gas turbines. Welding repairs are mostly used for non-rotating parts of the gas turbine and have been used for a long time in aerospace gas turbines due to requirements for lower weight high performance materials in the non-rotating parts of the engine. For stationary turbines the non-rotating parts are often less vulnerable cast materials and the need for welding repairs have been lower. By introduction of superalloys and other high performance materials also in the non rotating parts of stationary gas turbines the needs for repairs will increase.

3.5 Applications for processes and plants

A main goal for the research area is to study and demonstrate measures for increased efficiency and reliability as well as decreased O&M costs in existing and new full-scale power and CHP plants.

The major goal for the programme period 2010-2013 has been to study and evaluate advanced and high efficient concepts for CHP plants, “Reference Power Plants (RPP)”, for biomass fuels that could be demonstrated in a full scale plant to be commissioned around 2018.

[13] KME 406
[14] KME 506

The project has been co-financed by system and component manufacturers and energy utilities.[15]

The focus for biomass and waste fired power CHP plants is to enable increased steam data and mitigate the corrosion risk in superheaters, furnace and other exposed parts. KME projects have significantly improved the knowledge about corrosion mechanisms within high and mid temperature corrosion areas, especially assessment of materials for superheater tubes.

KME has also contributed in developing new boiler design features, such as placing the final superheater in the sand-loop of a CFB boiler instead of in the flue gas back pass. This together with material development has been a key for significantly elevating the steam temperature in biomass and especially for waste/RDF and waste wood fired boilers where the temperature can be increased by about 50°C.

Another important measure for mitigating high temperature corrosion and increasing steam temperature and/or increasing life of superheaters is to inject sulphur-based additives to the combustion process. Sulphur-based additives have been shown to be effective even at higher steam temperatures up to 600^{o}C. KME has contributed in both knowledge and development of patented methods. Other additives may also work, but have not been evaluated at higher steam temperatures.

Based on a number of material development projects KME has successively contributed to the improvement of materials that enables increased steam data in new plants and extended life in superheaters and waterwalls in both existing and new plants.

Waste fuels and RDF containing high amounts of critical compounds for high and mid temperature corrosion have limited the steam data and thereby the electrical efficiency. The above mentioned measures have already contributed to improvement of the efficiency in new plants. For example in CFB plants fired with municipal waste the temperature can be increased to 450°C, compared to 400 °C in conventional grate fired plants. KME has contributed in developing a new design for the final superheater. By introducing double tubing the tube surface temperature can be increased above the critical "window" for high temperature corrosion. This design has a potential for reaching even higher temperatures and could also be used for biomass plants.

3.5.1 Plants for Biomass and Waste fuels

A goal in the 2011-2013 programme has been to create and evaluate high efficient, and competitive, model concepts - Reference Power Plant(s) "RPP". The RPP model concept(s) aim to be realised in demonstration project(s) and will be moving target(s) that will be elaborated along with new findings and results from projects within the programme.[16] A number of advanced

[15] E.ON Climate & Renewables (UK), E.ON Värme AB, Fortum Värme AB, Göteborgs Energi AB, Kraftringen AB, Metso Power AB, Metso Power OY, Mälarenergi AB, Siemens Industrial Turbomachinery AB, Skellefteå Kraft AB, Svensk Fjärrvärme (Swedish District Heating Association), Söderenergi AB, Vattenfall AB, Växjö Energi AB, Öresundskraft AB

[16] KME 601

concepts have been studied to meet the project target of 3-4%-unit efficiency increase, compared to conventional plants.

The study focused on two selected fuel mixes; “Virgin” biomass fuels (basically forest residues) and “Wide range” fuel mix (represented by 75% recycled wood and 25% virgin biomass). Three different plant sizes; 100, 50 and 25 MW_e have been analysed. The heat production has been kept constant when calculating the plant performance for varied steam and feed-water data.

Several process layouts have been analyzed based on input from suppliers and heat balance calculations. Some of these have been selected for design studies by Metso for the boiler and by Siemens for the steam turbine package. Additional investment and operating costs for the advanced concepts have been compared with conventional plants for each size and fuel according to Table 3.1.

Table 3.1 Steam data steps studied for virgin fuels

Step	Pressure (°C)	Temp (bar)	RH Temp (bar)	Comment
Initial advanced target	190	600	600	Forced circulation, full steam temp to 80%
Advanced with target temp - RH	175	600	600	Circ. pumps not required
Advanced - RH	175	585	585	Flue gas circ. not required + improved operation range
Enhanced - RH	175	570	570	Commercial steam turbine temp data
Reheat and conventianal data	140	540	540	Conv. steam data
Target temp - No reheat	175	600		Smaller loop seal s.h. => less excess air and NOx
Avanced - No reheat	175	585		Improved operation flexibility without RH
Enhanced - No reheat	175	570		Commercial steam turbine temp data
Benchmark	140	540		Commercial proven for virgin biomass

Steam temperature up to 600ºC and admission pressure levels up to 190 bar have been studied for the biomass fired CHP plants, with and without reheat.

Siemens have developed steam turbines for super critical steam data with 620°C steam temperature, mainly for coal based power plants. KME has contributed in developing several new 9-12% Cr steels. The target has been to reach up to 650°C.

For small and mid-size steam turbines Siemens have assessed available steam turbine modules, today up to 175 bar 570°C and up to 190 bar 620/620 °C in progress. An important factor is the number of casings (meaning number of turbines) that will be required. The cost step is significant going from 1 to 2 casing and from 2 to 3 casing. 3-casing is required for 190 bar.

Virgin Biomass Fuels CHP

Based on design studies made by Metso and Siemens steam data up to 175 bar 600°C, and for the reheat option 175/46 bar 585/585°C have been regarded as technically feasible for sizes 50-100 MWe. The efficiency improvement compared to conventional plants (140 bar, 540°C) would be:

- 175 bar, 585/585 °C: +3,1%
- 175 bar, 600 °C: +2,3%

About the same improvements are achieved for 100 MWe and 50 MWe. Reheat has not been investigated for 25 MWe (not regarded as economically viable). However, there is limited efficiency improvement, about +1,3%-unit, without reheat, due to the lower temperature and higher relative boundary losses (shorter turbine blades).

The improvement potential compared to the benchmark for the most advanced cycle for both CHP and condensing process, i.e. 190 bar 600/600°C, is about 3,6%-units. This steam data would probably be of main interest for condensing plants. The temperature will have some drawbacks for CHP in terms part load performance, and will thereby be more of interest for condensing plants than for CHP.

Reheat will improve efficiency by about 1,2–1,4%-units, but is considered as an expensive measure that will require a long utilization time, as for condensing plants.

Table 3.2 Performance improvements for selected Virgin fuel options

VIRGIN BIOMASS FUELS		Reference 0			Advanced 1			Advanced 2		
		100 MWe	50 MWe	25 MWe	100 MWe	50 MWe	25 MWe	100 MWe	50 MWe	25 MWe
		LV0.1	MV0	SV0	LV1.0-3	MV5	SV1	LV11.4-2	MV4	
Steam temp		540	540	540	600	600	570	585/585	585/585	n.a.
Steam pressure		140	140	140	175	175	175	175/46	175/46	
Installed capacity										
	Electricity gross	102,1	49,6	25,8	114,6	55,4	27,8	119,6	57,2	
	Electricity net	94,2	45,4	23,7	105,3	50,7	25,3	110	52,7	
	Heat	170	85	45	170	85	45	170	85	
	Boiler output	272,1	134,6	71	284,6	140,4	73	289,6	142,2	
Fuel input		298,6	148,9	78,5	311,6	155,2	80,6	318,2	155,9	
Gross efficiency		34,2%	33,3%	32,9%	36,8%	35,7%	34,5%	37,6%	36,7%	
Net efficiency		31,6%	30,5%	30,1%	33,8%	32,7%	31,4%	34,6%	33,8%	
Boiler efficiency		91,1%	90,4%	90,2%	91,3%	90,5%	90,4%	91,0%	91,2%	
Fuel efficiency		88,5%	87,6%	87,4%	88,4%	87,4%	87,3%	88,0%	88,3%	

For the 600°C concepts the life time for the final superheater has not yet been proven in a real environment with renewable fuels. Proposed material in the design study has been SA-213TP310HCbN (HR3C) or equivalent. More detailed strength calculations and tests will be required for the final design.

A steam turbine temperature of 600°C is proven for large plants but not proven in smaller sizes. Data is here based on existing modules and experience from large steam turbines.

For Swedish conditions larger (100 MWe) advanced concepts without reheat (175 bar, 600°C) are competitive against the conventional plants, under normal CHP operational conditions. Increasing temperature and reheat will introduce operational flexibility limitations, especially part load efficiency and minimum load. Reheat requires longer utilization time, and is more suitable for condensing plants. Smaller plants are for the assumed conditions and prices not competitive against the conventional plant. However the differences are small.

Wide Fuel Range CHP

The number of challenges increases for the wide fuel range, for the studied case defined as 75% waste wood and 25% virgin wood. In addition to the high temperature corrosion risk, among other risks, mid temperature corrosion (mainly furnace corrosion) and cold end corrosion, have to be considered in the boiler design.

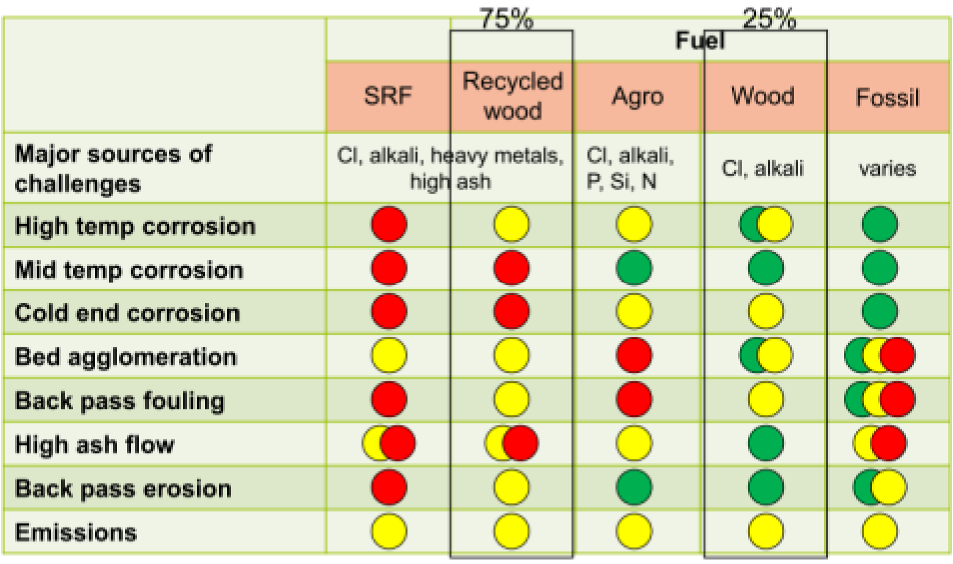

Figure 3.4 Major challenges for different fuels

Selected concepts (160 bar 560°C and 160/44 bar 560/560 °C) cases have been regarded as technically feasible, but the significant increase in pressure causes a temperature increase for furnace and evaporation surfaces, which calls for measures in order to mitigate the water wall corrosion risk in the proposed boiler design. Measures studied include protecting of the waterwalls with refractory or/and metal cladding (welding) in critical surfaces. These measures have to be further tested in terms of reliability, maintenance, etc. Based on other KME projects[17] future solutions could be new additives (kaolin, sewage sludge) or new materials. Solving this would mean a major step forward for the efficiency of waste wood power and CHP plants.

The efficiency improvement for main advanced steam data options compared to the benchmark is higher for wide range fuels than for virgin fuels, 2,8% - 3,8% compared to 2,3% - 3,1%.

The reheat alternative looks promising (+38% efficiency). The same conclusion is however valid as for the virgin fuels, i.e. reheat will require long utilization times to be competitive.

Financially the advanced 50 MW_e concept without reheat (160 bar, 560°C) is more profitable than the conventional plant (100 bar, 500°C), for base case conditions. It seems also to be robust against reasonable changes in electricity and fuel prices as well as changes in variable cost, and unforeseen increases of Capex. Also the advanced smaller plant of 25 MW is competitive against the conventional plant, if the utilization time is at least 6000 hours per year.

General CHP

Operational conditions as well as fuel and electricity prices including support mechanisms are of course essential for the total profitability which of course

[17] KME 512

is the major driver for demonstration of advanced plants. Electricity prices vary with the current demand and market situation, as well as the support systems in different countries.

There is no doubt that plants with an electric generation capacity of 50 MWe and below, using a wide range fuel mix, have more interesting potential for enhanced concepts than similar plants using virgin fuels.

An important finding is that the extra operation and maintenance costs (Opex) will (in terms of net present value) be as important as the extra Capex, required for an advanced plant, when analyzing the competiveness.

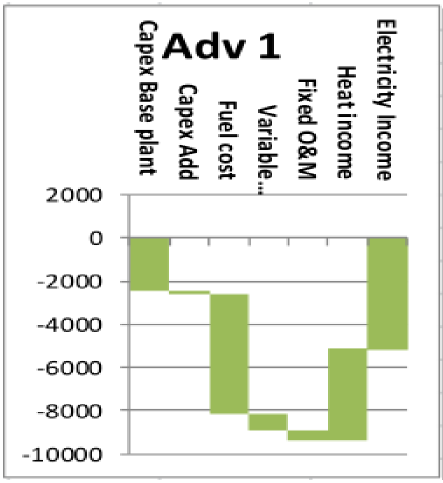

Figure 3.5 Net present value (MSEK) per main cost/income component for 100 MW CHP with Virgin fuels

The major challenges for future development are hereby reducing the difference in both Capex and Opex, between the conventional and advanced concepts. Another major challenge is of course to eliminate possible additional availability risks.

Condensing plants

Condensing plants have been studied for the largest capacity (> 100 MWe) for virgin fuels in the process analysis, although the financial assessment has been focusing on CHP plants. However, calculation for one selected case indicates that advanced steam data would be more profitable for condensing plants than for CHP.

3.5.2 Risk management in the demonstration phase

To support the goal of finding a site and host for a full-scale demonstration of a CHP plant with advanced steam data, risks that can be present <u>during a demonstration phase</u> of a biomass plant have been studied.[18]

Results from the initial assessment[19] indicated that a detailed study of the technical and economic risks of the developed generic plant

[18] KME 609
[19] KME 601

concepts was required as a part of the decision basis for the potential demonstration plant. A study[20] was performed with the target to make a more thorough evaluation of the technical and economic risks.

Two promising concepts were selected; Virgin fuels with steam data 175 bar 600°C and wide fuel range with steam data 160 bar 560°C.

Included objectives were to define non-conventional parts that need to be demonstrated, identify technical risks for these parts and quantify the risks in monetary terms. An additional task was to evaluate a “fall-back” option to be used for reducing the risk if there are operational problems at the advanced steam data level.

Finally the project comprised an investigation of how to finance the additional risk for a demonstration plant and to evaluate economical/project risks for the plant e.g. procurement, guarantees and risk sharing.

For the virgin fuel, the major risks are creep and fatigue of the final superheater, availability of the turbine, steam side oxidation, and carry over from steam side oxidation on the superheater and steam turbine. The underlying design parameter for these risks is the increased steam temperature of 600°C and introduction of new materials both for the final super heater and turbine.

The most important parameter for the wide fuel case is the increased steam pressure, resulting in an elevated temperature in the furnace walls, thus increasing the risk for mid-temperature corrosion. Proposed protection measures are not fully proven today.

The risk is higher for the wide range fuel concept than for the virgin fuel concept. On the other hand the profitability potential is higher for the wide fuels range concept than for the virgin.

It is of course important that the risks can be further assessed and reduced by new tests in existing plants and in the detailed design before the demonstration plant will be built.

The relative size of the required extra capital funding, to eliminate the negative impact from the most probable risk value, is between 17 % and 32 % of the additional plant investment needed when going from conventional to advanced steam data. The levels of the capital funding are in the same range as the funding possibilities that have been identified. The most important funding sources are Horizon 2020 and the Swedish Energy Agency.

For both fuel cases fall-back options have been defined with the prerequisites to identify a fail-safe mode with the highest economic feasibility.

A safe and economic feasible fall-back option for the wide fuel case is more difficult than for the virgin biomass case, since also the pressure is very elevated in the advanced concepts compared to reference case. The fall-back option for the wide fuel case needs to be further developed.

The concept must also be commercially attractive enough for a buyer and supplier to be willing to take the risk of engaging in a demonstration

[20] KME-609

project. Besides the technical risks some economical/project risks have therefore been addressed.

- Certain plant sections will not be covered by normal commercial guarantees. It is recommended that these parts are handled by risk sharing between supplier and buyer. One suggested measure is to set up a monitoring program linked with a risk sharing/bonus system. Probably the most important measure to handle the risks and guarantee issues in the project, is however to perform up-front testing of the advanced design measures.
- Multiple contract for procurement instead of turn-key contract and advanced steam data as optional is suggested, both as a means to quantify the risks of the advanced concept in monetary terms for a final evaluation, and to increase the possible number of bidders.

The evaluation of the commercial risks has been seen as a good completion of the development work with respect to development of processes and plants performed during the program period 2010-2013.

4 Implementation - possibilities, problem areas, restrictions and main challenges

4.1 Progress in co-operation

Experience from previous KME stages shows that KME offers opportunities for a forum where material producers, system and component manufacturers and end users meet to discuss and consider problems and possible solutions together with experienced and competent researchers. KME assists in this sense in creating a unified understanding of problem scenarios and increases the possibility of new solutions.

Material developers and manufacturers – e.g. Sandvik Materials Technology, Sandvik Heating Technology, MH-Engineering

- Material developers and manufacturers together with utilities define the challenges which materials should manage for future material development with a view to improving performance and efficiency.
- Creates opportunities to test new and commercial materials in different environments.

System and Component manufacturers – e.g. Siemens, Andritz, Völund, Foster Wheeler, Metso (Valmet), GKN

- In projects with material manufacturers and utilities constraints are defined on materials in different environments. The environment's influence on materials for new plant design solutions offering enhanced performance and efficiency is considered.
- Creates opportunity for evaluation and development reached by the material, joining and manufacturing methods, and design solutions for new applications in various constructions.

Utilities (end-users) – 14 Nordic energy utilities[21] and Swedish District Heating Association

- Along with material and system manufacturers new materials and design solutions can be tested in plants under various combustion environments to reduce operation and maintenance costs.
- Evaluate the mechanisms that cause problems in the flue gas environment and test the tools to change the combustion chemistry by optimizing the fuel mix or utilization of additives.

[21] Dong Energy, Fortum, E.ON, Vattenfall, Göteborgs Energi, Mälarenergi, Kraftringen, Söderenergi, Tekniska Verken Linköping, Jämtkraft, Öresundskraft, Gävle Energi, Karlstad Energi

Universities and Research Centres – e.g. HTC, Chalmers University, Linköping University, Royal Institute of Technology, Lund University, SP, KIMAB

- The KME programme contributes to long-term creation of competence within the fields of process, combustion, and materials technology linked to energy applications. Thanks to the long-term nature of the programme's research, senior and newly qualified doctoral researchers will acquire even greater levels of competence, as well as knowledge in the field, from which industrial companies stand to benefit.
- Close co-operation with industry means that the academic researchers work with industrially relevant problems and are more likely to be employed by industry after qualification

The KME co-operation has led to numerous new opportunities for improvement in design and operation of existing as well as new plants. A number of examples are recognized in the following. However, as commented by one of the partners, one of the main benefits from the co-operation is the interesting development work with skilled and motivated partners.

One consortium member since several program stages, Metso (Valmet) summarizes the contribution from previous KME stages as follows:

- KME has improved our understanding on customer's and turbine supplier's demands, expectations and technical design aspects so that our boiler plant solution can be better optimized for the purpose and for the whole power plant concept;
- KME has contributed to improve Metso´s conceptual design and knowledge for high efficiency (high steam data) solutions for virgin and demolition wood boilers; and
- KME has contributed to improved understanding on how different technical details are influencing the CAPEX, OPEX and feasibility of the whole power plant.

4.2 Improvement of existing plants

4.2.1 Condensing plants

Co-firing of biomass, especially wood pellets, in coal fired plants, is an effective way to reduce CO2 emissions in existing plants.

In coal plants there is today a natural limit of about 10% admixture in order to reuse the coal ash in the cement industry, which is normally done.

Depending on the share of biomass as well as the fuel and ash properties there is a risk for fouling and corrosion in co-firing. High temperature corrosion in superheaters, furnace (waterwall) corrosion and low temperature corrosion risks have to be mitigated. In addition to this there is a risk for clogging of catalysts. However the sulphur content in the coal will act as a sulphur based additive which significantly reduces the problems with high temperature corrosion. Shares in the range of 70% could therefore be possible in some cases, considering high temperature corrosion problems.

The problems with alkali driven high temperature corrosion will increase in cases of co-firing biomass with natural gas.

At present there are no practical means to determine the allowable mixing percentage for a boiler in general terms, and the impact on the maintenance and availability, besides tests at the actual site. Knowledge and findings from KME activities can be used to optimize the fuel mix, based on fuel analyses and actual design. On-line monitoring, additive selection and additive control, coatings, replacement of tube materials are some examples.

4.2.2 Boilers

Since the fuel costs are a major part of the total generation cost in CHP or power only plants a common and natural activity for a plant owner is to seek cheaper fuels. This is especially important when electricity prices are low and has resulted in the successive introduction of a larger share of waste derived fuels in boilers, which were originally designed for virgin fuels. These are fuels like waste (demolition) wood of different qualities, paper-wood-plastics fractions; refuse derived fuels (REF/RDF) etc. All these fuels have higher contents of critical compounds, which increase the risk for high temperature corrosion, erosion, furnace corrosion and low temperature corrosion. In addition, these “difficult” fuels are more challenging in terms of combustion control (even combustion), emission control and wear in the fuel and ash handling systems.

The expected profit in introducing cheap fuels can in the worst case in the long run result in a NPV[22] loss, due to increased unavailability and high maintenance and repair costs. In addition to this there is a risk for losing production capacity, in power and in some cases total boiler capacity, if reduction of steam temperature and/or pressure is required. The challenges for each plant are of course very dependent on the actual boiler design and the extent of fuel conversion.

KME has contributed in developing several methods and design features for mitigating fouling, corrosion and erosion in different parts of the boiler. By utilizing this accumulated knowledge, test results and experience from other similar conversion projects there is a good chance for increasing the fuel flexibility and profitability of the plant. Some examples are:

- Contributed to Vattenfall's work with its patented product ChlorOut, and additives that are added to the flue gas to reduce superheater corrosion.
- Validation of correlations and models for prediction of rate of corrosion, which have led to the development of an advanced computational model based on chemical equilibrium calculations for materials in boilers.
- Reduction of fireside corrosion with coatings of new alloys.
- Selection of more cost-effective materials for superheater replacement.
- The effect of additives (additives, e.g. digested sewage sludge) to biofuel to reduce corrosion.

[22] Net Present Value

4.2.3 Gas Turbines

The service schedule of a gas turbine (and plant) follows a predefined set of cycles. An old rule of thumb is that the maintenance cost is approximately twice the initial investment cost during the plant life. The total world-wide gas turbine fleet is in the order of 47,000 units and the total value of the gas turbine after-market was 2009 EUR 13.8 billion.[23] The after-market is, indeed, valuable to the manufacturers since all 47,000 units require maintenance on a regular basis.

The Swedish part of Siemens, as well as other gas turbine manufacturers, is continuously focused on product development and improvement. Continued enhancement of existing products and services is an important part of the development concept. The drivers for modification and upgrade of existing plants are emissions reduction, extension of life cycle and time between overhauls and improved maintainability and repair of hot gas path components. Together, these upgrades play an important role in power plants' competitiveness and profitability improvement.

For emissions reduction the development of the DLE burner has been vital. Today the DLE burner is standard design, and since the introduction in 1986 the NOx level has been decreased from 75 ppm to 10 ppm with new materials and improved design. The benefits of the development are also required for existing plants and concepts for upgrade of the DLE burner have been introduced also for the after-sales market. Metallography tests and evaluations performed in KME projects[24] have been guiding the selection of materials resistant to carburising conditions which may occur in the burner.

Efforts for the extension of engine life-time and reduction of maintenance downtime are dependent on previous operation profiles and history of the installation. Maintenance cost reduction is primarily achieved via repair and refurbishment of expensive turbine components. It is mainly concentrated around the hot gas path components, which normally require replacement on a regular basis. KME projects have contributed to improved reconditioning processes for a number of hot gas path components by the improvement of weldability for repair of burners and vanes and recoating of burner materials with the use of new environmentally friendly recoating technologies.

By these measures life time extensions of up to 50% can be achieved, from for example 120,000 equivalent operating hours (EOH) up to 180,000 EOH. Extension of maintenance intervals with 67% can be achieved, mainly for plants with base-load operation profile and latest component design.[25]

Current customer demands are to a great extent related to more flexible operation and a movement towards cyclic operation modes. In order to respond to these demands modifications of components are required, modifications that are highly dependent on TMF design tools developed in several consecutive KME projects.

[23] Genrup M, Thern M, Gas Turbine Developments 2012-2014, Elforsk Report 13:31
[24] KME 409
[25] Navrotsky V, Gas turbine performance and maintenance continous improvement, VGB Conference Gas Turbines and Operation of Gas turbines 2013, 11-12 June 2013, Friedrichshafen, Germany

4.3 Construction of new plants

4.3.1 Condensing steam turbine power plants

For large condensing plants and especially coal fired power plants Ultra Critical steam data is commercially available today, with efficiencies up to 47% for hard coal. This would open up for CCS (Carbon dioxide Capture and Storage) which with this steam data would reach a net efficiency of about 38%.

The research programmes COMTES700/COMTES+ with steam data up to 700°C/720°C and 350bar would reach 50% net efficiency (without CCS). The COMTES programmes are very much directed towards demonstration of materials development, manufacture and evaluation for different components in both boiler and steam turbine systems.

The driving forces for implementing both the 700°C programmes and CCS are for the moment weak. Falling demand for electricity in conjunction with overcapacity in production has resulted in low electricity prices so investment in new coal-based plants is not financially viable. This is considered unlikely to change in the near future.

Also for new condensing plant co-firing with a share of biomass could be of interest, with risks for high temperature corrosion in superheaters, furnace (waterwall) corrosion and low temperature corrosion as well as clogging of catalysts. Knowledge, findings and measures from KME could be important for design and optimization of fuel mix as well as finding mitigation measures.

4.3.2 Boilers

A usual requirement for new CHP and power generation plants is fuel flexibility; the fuel is the dominating cost factor for the plant and the possibility to use cheaper fuels is regarded as important. Another important factor is the uncertainty of available and therefore price development of future biomass and waste fuels.

In order to increase electrical efficiency significantly in new plants for a certain fuel mix, steam data have to be increased.

Increased availability and decreased maintenance costs for a certain fuel mix, but also in combination with enhanced steam data and/or increased fuel flexibility is of great importance for the profitability of new plants.

Findings from the KME activities in cooperation between industry, plant owners and universities are successively implemented for new plants, exemplified by:

- Materials with increased resistance against corrosion and erosion
- Manufacturing methods, weldability, assembly, replacement of super heater bundles based on new materials
- Additives for mitigating high temperature corrosion and furnace corrosion
- Protection of waterwalls in furnace and other parts against corrosion (such as Inconel cladding or metal spray) and erosion (refractories)
- Design features for final superheaters in CFB boilers

4.3.3 Steam Turbines

Even if enhanced steam data will be feasible for biomass and waste fired boilers limits could occur in steam turbines, in terms of both temperature and pressure. Some of the challenges at enhanced steam data are:

- Relatively high boundary losses in HP-stages reduce the efficiency at high pressure
- Moisture in last turbine stages at high admission pressure
- Reheat means
  - A very expensive design for smaller units
  - Reduced part load performance - Not suitable for many district heating applications
- Creep strength in steam pipes and turbine for high temperatures (600°C)
- High pressure results in high temperature in boiling tubes
- Steam side corrosion in high temperature tubes
- Cost optimization in order to compete with systems for conventional steam data. Going from 1- to 2-casing (turbine) solution, as well as going from 2- to 3-casing solution are very expensive steps.

There is still a potential for improvements in the isentropic efficiency for smaller plants, since there has been a lack of economic driving forces.

Siemens have shown that it is possible to increase the steam data for smaller turbines up to 175 bar 600°C based on current technology derived from larger plants.

Technical challenges are steam side corrosion. Protective coatings are close to commercialization.

Cost optimization for smaller CHP steam turbines will be important in order to compete with heat only boilers.

4.3.4 Gas Turbines

All major gas turbine manufacturers have developed air cooled gas turbines for combined cycles with efficiency around 61 percent. Several of them can offer plants able to do a hot restart within 30 minutes to, more or less, full load.

The role of the combined cycle will probably change from being a natural gas

fired mid or base load plant to either a fuel-flexible base load or a plant for covering the daily variations (i.e. operational flexibility). The introduction of high levels of volatile wind and solar power capacity will create a market for fast start and ramping production. The gas turbine is the only technology that is capable of meeting the future flexibility requirements due to this high volatile renewable penetration.

The key to 61 percent efficiency is high performing gas turbines, which includes components, pressure ratio and firing temperature. In addition, the exhaust temperature has to be at a level for maximum bottoming cycle performance. Today, most manufacturers have 600°C steam turbine admission temperature capability and the optimum exhaust gas temperature should therefore be on the order of 25-30°C higher. 26

The main features of a high performing combined cycle are presented in Figure 4.1.

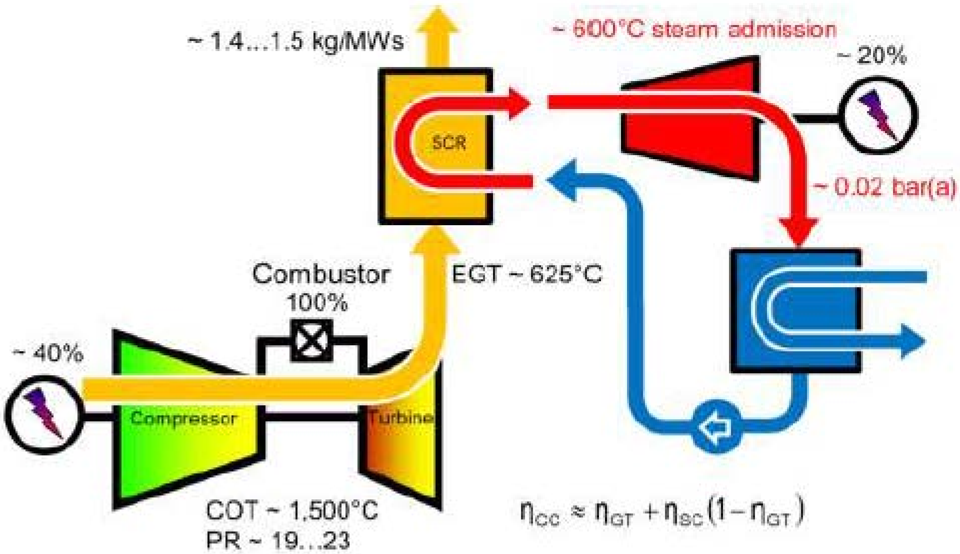

Figure 4.1 High performing GTCC features (Source: Genrup M, Thern M, Gas Turbine developments 2012-2014, Elforsk Report 13:31)

Mid-size gas turbines will most likely stay below 1400 °C combustor outlet temperature (COT). Higher COT levels will force the steam turbines to 600 °C admission temperatures, calling for usage of higher chromium alloys in the hot sections. Operational flexibility requirements will be in the range of 30 minutes hot-start and steep ramp-rates.

The KME research efforts have been very well adapted to this overall development by initiatives in development of high strength single crystalline materials and coatings, which are together with the design of the cooling measures key elements to the performing edge of new gas turbines. High temperature materials with both good oxidation and corrosion resistance have been developed. Temperature distribution problems, typically manifested as cracks near the fillets in the first vane segments, have been addressed by comprehensive research to handle and minimize thermo-mechanical fatigue (TMF). Thus the established TMF results have been successfully introduced as design criteria by Siemens for improved design of the most temperature-exposed details of new gas turbines.

The trend with higher temperature levels and more exotic materials has to be accompanied by effective repair technologies for reasonable maintenance costs, which has attracted the attention by KME projects dealing with improved weldability and methods for verification of welding methods for single crystalline materials.

[26] Genrup M, Thern M, Gas Turbine Developments 2012-2014, Elforsk Report 13:31

5 Continued future KME efforts

5.1 KME in the research front

Monitoring and evaluation is an integral part of the KME programme. Evaluations are regularly made by an evaluation group with international experts, appointed by the Swedish Energy Agency in consultation with industry and universities, in the end of each programme stage, consequently every four years.

According to the latest international evaluation, performed in the end of the fifth programme stage in 2013, the joint expert opinion is expressed as

- KME is a well-functioning research programme with an obvious goal, active stakeholders and an administrative structure and function that has to be considered as very good.
- It is obvious that KME contributes to integration between industry and universities in a very positive way.
- The research activities are in general on an excellent scientific level. Some of the projects are to be classified as top class research projects in an international perspective.

Without performing a more detailed study and comparison of achieved applications of results from open research programmes, KME is considered as an achievement of professional recognition. The continuity of the programme as well as adaption to changing market conditions contributes to its performance.

5.2 Prioritized R&D areas for the next programme stage

The coming KME programme stage 2014-2018 is divided into two research areas, Development of Process and Plant Technology and Development of Materials Technology. The starting point shared by both areas is the fact that materials technology process development should help to ensure that renewable fuels and waste can be used efficiently in order to produce electricity and heat within thermal energy processes. This involves high fuel flexibility, good part-load characteristics and minimal impact on the environment. The materials technology research area should constitute a knowledge base for demonstration and implementation of new technology in the process and plant technology research area.

As for previous programme stages the results from the projects should be intended for application within five to ten years.

5.2.1 Process and plant engineering development

The focus in this area is to demonstrate and implement more effective and profitable thermal processes for electricity and heat production in both existing and new plants. The area includes engineering solutions, systems engineering and economic analyzes, and may refer to:

- Via the model and reference plant concepts to show how the program results can be of use and relevance to plants, and to identify further research and development on issues improving fuel flexibility and operational flexibility.
- Propose and validate cost-effective solutions for improved operations and materials reducing corrosion and erosion risks.
- Verify that the steam temperature can be increased by at least 40° C , from about 540 to 580° C with pure biofuels (wood fuels) , and from about 450 to 500° C with fractions (RDF) as fuel by material tests in pilot scale with conventional superheater materials in existing boilers.
- Develop procedures and guidelines for how new materials can be used in installations, including control and monitoring systems.
- Present the itinerary for how plants in Sweden can reach higher steam data – a similar long-term vision of 3-4 percentage points higher electrical efficiency than the best technology for granted fuel today.
- Supporting demonstration projects of cogeneration plants, or subsystems of existing facilities, with higher steam data.

5.2.2 Materials Technology Development

In the area of materials technology development efforts are directed at developing material solutions for boilers and performance enhancing material issues of gas turbines and steam turbines. This area means that more fundamental knowledge of materials is developed to be applied and demonstrated in new advanced processes and applications for energy conversion. Efforts in the field of materials engineering solutions for boilers may relate to:

- Solutions to minimize problems with high temperature corrosion and erosion in boiler installations and greater understanding of the conditions under which the problems arise.
- Measures to prevent problems with low temperature corrosion in economizers and air preheaters and increased knowledge of the conditions under which the problem occurs.
- Test and evaluate various material groups (alumina-forming alloys, NiCrFe materials, etc.) for solid components , composite materials and /or coatings in different environments, operating conditions and temperature ranges in order to develop materials with improved properties.
- Application tests of a steam loop attached to an existing superheater in order to examine the conditions for higher steam data (600 ° C steam temperature for pure biofuels).
- Conduct studies in lab scale to evaluate the mechanisms that have greatest impact on the material's mechanical lifespan relevant to new

demands on the materials at higher steam pressure and steam temperatures.

- Expand knowledge of the technical problems and risks related to increased fuel flexibility. Understanding the conditions under which problems arise, analyze the dynamic corrosion process (e.g. corrosion memory effect) and possible measures to prevent problems.
- Materials Technical Development for converting boilers from fossil to biomass-fueled plants, incl. admixture of renewable fuels.
- Materials Technical Development for gasification processes.

Efforts in the area of material issues of gas turbines and steam turbines may refer to:

- Test and evaluate materials and coatings for efficient gas turbines optimized for cyclic operation to balance the production of electricity from solar and wind power
- Develop improved blading profiles and advanced technologies for industrial steam turbines in order to improve turbine efficiency.
- Develop methods to quantify weldability and forming, i.e. how new advanced materials can be joined together with more conventional materials to achieve cost-effective solutions for efficient energy plants.
- Identify and create an understanding of how the materials microstructure develops with time and temperature for nickel base alloys, and measures for preventing possible problems.
- Evaluate the impact of long-term exposure on the mechanical properties of nickel-based alloys and evaluate applicability of particle growth laws for predicting the microstructure during exposure.
- Operating flexibility, and the use of renewable fuels (biogas, hydrogen and liquid biofuels) and fuel flexibility of gas turbines.

5.3 Demonstration – possibilities and requirements

One of goals for KME has been and still is to support demonstration projects of high efficient and/or fuel flexible cogeneration plants, or subsystems and measures in existing facilities for widening the fuel flexibility or improving efficiency and availability.

The demonstration phase is of course of great importance in order to reach a commercial phase. KME is an ideal platform for this collaboration between R&D organisations, industry and end-users.

In order to demonstrate new designs and new solutions in full scale the timing has to be right in terms of new plant planning and the drive for high efficiency and fuel flexibility.

The drivers for mid- and small size high efficient cogeneration plants are directly connected to the electricity price but often also to a long-term support system such as green certificates, feed-in tariffs, etc. When the electricity price is falling, which has been the case in the latest period, the incentive for the end-user to take risks for demonstrating a concept with enhanced steam data is lower. Significant Capex support will then be of great importance for minimizing the risk for the end-user.

It is however in the long run important to use the limited fuel sources as efficiently as possible, which also includes producing maximum power from limited heat sinks where heat can be utilized, such as district heating systems and industry processes for cogeneration.

An important drive is to improve, or maintain availability with more difficult fuels, as well decreasing operation and maintenance costs.

The drive for fuel flexibility and the possibility to use difficult fuels will probably still be as significant in the future as it is today. Materials, coatings, additives, repair methods, fuel optimisation, combustion monitoring & control, and improved design of systems have to be tested and demonstrated, which could be done in both existing and new plants. For these activities the KME program can offer important contributions.

Appendices

KME Projects 2010–2013

Programme area Material Base Programme (MATBAS)					
Project	**Performed by**	**Industry partners**	**Project name**	**Project Goal**	**Project manager**
KME-501	Linköping University	AB Sandvik Materials Technology	Long term high temperature behaviour of advanced heat resistant materials	The purposes of this project are to evaluate stress relaxation cracking behavior, tensile deformation and cracking behavior with very slow strain rate for advanced heat resistant materials	Sten Johansson
KME-502	Linköping University	Siemens	Fatigue in nickel-based superalloys under LCF and TMF conditions	The project is a continuation of the previous projects KME-403 and KME-410 and deals with fatigue in nickel-based superalloys under conditions of low-cycle fatigue (LCF) and thermo-mechanical fatigue (TMF) with focus on component-near conditions.	Johan Moverare
KME-503	Linköping University	Siemens	New Durable MCrAlX Coatings for High Temperature and Corrosive Environment Applications in Advanced Engines	The aim of the project is to develop new durable MCrAlX coatings for use as protective overlays and bondcoats in TBC systems by incorporating recent research results and considering the increased turbine requirements	Ru Peng
KME-504	Swerea KIMAB, SP Technical Research Institute	Vattenfall	Correlation between deposit chemistry and initial corrosion of super heaters	The overall objectives of the project are to improve the description of the chemistry of a deposit and link it to the initial corrosion.	Rikard Norling
KME-505	Chalmers	Siemens, Sandvik Heating Technology	Properties of alloyed $MoSi_2$ matrix composite for hot corrosion and elevated temperature components of gas turbine	Evaluation of mechanical and thermal properties of the $(Mo_{0.9}Cr_{0.1})Si_2$+15 vol.-% ZrO_2 composite. Comparison with other commercial candidate materials and different mechanical tests performed at ambient and high temperature, together with thermal cycling tests at high temperature.	Yiming Yao
KME-506	Chalmers	GKN Aerospace	Weldability Limits for Superalloys in High Temperature Applications for Gas Turbines	Find superalloy combinations, welding methods and appropriate heat treatment schedules to increase the potential for hot gas turbine structures applications	Lars Nyborg
KME-507	HTC	Sandvik Heating Technology, E.ON Värme, Vattenfall and Metso Power	FeCrAl alloys for components in biomass and refuse fueled boilers - prestudy	Identify and understand the usability and the limitations of alumina forming materials as components in biomass- and waste fired combustion plant.	Kristina Hellström

KME-508	KIMAB, SP and KTH	Sandvik Heating Technology, Sandvik Materials Technology, Outokumpu, E.ON Värme, Vattenfall, E.ON Climate and Renewables and Metso Power	Furnace wall corrosion in biomass and waste-fired boilers at higher steam pressures	Give recommendations about how to avoid water wall corrosion at increased boiler electrical efficiency/increased steam data when burning biomass and waste wood mixes.	Pamela Henderson
KME-509	HTC	E.ON Värme and Metso Power	Concentrated approach on super heater corrosion in boilers fueled with biomass and refuse	Improve plant economy by enabling an increased electricity production and enhancing fuel flexibility.	Jesper Liske
KME-510	Chalmers	Siemens and DongEnergy	Design of a new generation of 12% chromium steels	Development of a new generation of martensitic chromium steels that use Z-phase as a strengthening rather than weakening phase.	Hans-Olof Andrén
KME-511	HTC	DongEnergy	Critical corrosion phenomena in power generation from biomass – Identification of chlorine resistant high temperature coatings/materials	Identify possible coatings/materials for superheater tubes, which allows an outlet steam temperature of at least 580°C on biomass converted fossil-fired units.	Torbjörn Jonsson, HTC
KME-512	Vattenfall Research and Development, SP, Åbo Akademi	E.ON Värme Sverige, E.ON Climate and Renewables, Metso, Outokumpu, Sandvik Heating Technology	Fuel additives to reduce corrosion at elevated steam data in biomass boilers	Identify and evaluate the use of additives and fuel blends to reduce furnace wall, and possibly also superheater, corrosion for wide biomass fuel mixes including waste wood. To give a recommendation of the identified additives.	Maria Jonsson, Vattenfall
KME-514	HTC	Fortum	Increased electrical efficiency and service life assessment of super heaters from combustion of difficult fuels	Providing a model for more reliable assessments of the service life of superheaters	Jesper Liske, HTC
KME-515	Vattenfall and SP	Vattenfall	Furnace wall corrosion in biomass and waste- fired boilers at higher steam pressures	Ash particle measurements with impactor technology, as an extension of KME 508.	Pamela Henderson, Vattenfall
KME-518	Chalmers	GKN Aerospace	Weldability of superalloys - physical metallurgy extension	Identify how results generated from laboratory experiments and the Varestraint method could best contribute to future process modeling. Project is an extension of KME-506.	Lars Nyborg
KME-519	HTC	Sandvik Heating Technology	FeCrAl alloys as components in biomass- and waste fired boilers with sulphur additives	Identify and understand the usability and the limitations of alumina forming materials as components in biomass- and waste fired boilers, and in particular investigate the effect of sulfur additions.	Kristina Hellström, HTC

KME-520	Linköping University	Siemens	Extension of the project KME503 on "New Durable MCrAlX Coatings for High Temperature and Corrosive Environment Applications in Advanced Engines	Verification of the thermodynamic simulations by high resolution micro-structure and chemical composition analysis and to obtain experimental data for certain X-elements needed for the chemical composition optimization in KME 503	Ru Peng
KME-521	Linköping University	Sandvik Heating Technology	Thermomechanical fatigue in virgin and aged stainless steels	Evaluation of TMF testing on six different austenitic stainless steels in order to their susceptibility to different strain and temperature cycles.	Johan Moverare
Programme area More Effective Power Production (RPP)					
Project	**Performed by**	**Industry partners**	**Project name**	**Project Goal**	**Project manager**
KME-601	Vattenfall Power Consutant/Pöyry Swedpower, Konsultbyrån Skog KB	Siemens, Metso Power, Vattenfall, E.ON Värme, Fortum Värme, Kraftringen Produktion, Svensk Fjärrvärme, Göteborg Energi, Mälarenergi, Skellefteå Kraft, Växjö Energi, Öresundskraft, Söderenergi	More Effective Power Production from Renewable Fuels – Reference Power Plant (RPP)	The goal for the "RPP project" is to create and update Reference Power Plant(s) concepts in cooperation and dialogue with the steering group and the KME stakeholders.	Erik Skog
KME-607	Magnus Genrup, Lund University	Siemens Industry Turbine	Improved steam turbine design for optimum efficiency and reduced cost of ownership	The project will evaluate the maximum cost effective efficiency potential of industrial steam turbines, by introducing improved blade profiles and advanced blade stacking technologies	Magnus Genrup
KME-608	Pöyry Swedpower, HTC Chalmers	E.ON Värme, E.ON Climate and Renewables, Sandvik MT	Study of corrosion memory in boiler heat surfaces by field tests with biomass fuel mixes including sulphur and refuse fractions	Investigate the three main questions: can low corrosion rate be maintained when conditions are changed, is there a memory effect, and is there an incubation time	Tom Sandberg/Lars Wrangensten
KME-609	Vattenfall R&D, Pöyry Swedpower	Vattenfall, E.ON, Siemens, Metso Power	Technical and economical risks for plant concepts with advanced steam data for biomass-fired CHP demonstration plant	Make a evaluation of the technical and economical risks for the generic plant concepts developed in KME-601. Define what parts of the plant that are non-conventional, evaluate a "fall-back" option, investigate how to finance the additional risks	Raziyeh Khodayari

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