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Indirekte biomassefyret gasturbine

Afslutningsrapport for EFP-projekt: Projekt inden for procesintegration

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MEK

Energiteknik

MEK–ET–2002–01

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26. februar 2002

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af Brian Elmegaard og Bjørn Qvale

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Forord

I det følgende slutrapporteres EFP-projektet "Projekt inden for procesintegration". Projektleder har været Professor Bjørn Qvale, mens yderligere tre forskningsmedarbejdere, Martin Wittrup Fock, Brian Elmegaard og Falko Jens Wagner, har været engageret på projektet.
Projektets hovedformål har været at udvikle systemer for anvendelse af gasturbiner i forbindelse med biomassebaseret kraft-kraftvarmeproduktion. Fokus har været på Indirekte Fyrede Gasturbiner (IFGT).
Det foreliggende projekt indgår i et længerevarende forløb som har strakt sig over et antal år. Vore studier af den Indirekte Fyrede Gas Turbine startede med to eksamensprojekter (se Referencelisten). Det projekt som nu rapporteres, blev påbegynt ved hjælp af interne DTU-midler. Martin Wittrup Fock som var ansat på projektet forlod DTU 15/11-98. Indtil dette tidspunkt var der kun trukket på interne DTU-midler (Stipendium og barselorlov), interne Institut-midler fra MEK-instituttet, og stipendium fra Nordisk Energiforskningsprogram(NEFP – Procesintegration).
Da Martin Wittrup Fock forlod projektet godkendte styregruppen at man af hensyn til den regnskabsmæssige overskuelighed, 1/1-98 som nominel skæringsdato for start af projektet. Som skæringsdato for afslutning af projektet har vi valgt 1/10-2001. Projektet fortsætter dog i dag med økonomisk støtte fra andre kilder.

Resumé

Rapporten beskriver et projekt udført på Danmarks Tekniske Universitet, Institut for Mekanik, Energi og Konstruktion. Projektets formål har været at udvikle kraftværksprocesser baseret på indirekte fyring af gasturbiner med biomasse. Fokus har været på gasturbiner i lille skala, såkaldte mikroturbiner. Disse turbiner er for nylig markedsført og giver forhåbning om at kunne opnå en tilstrækkelig virkningsgrad for den specielle kombination af gasturbiner og biomasse.

Virkningsgraden for indirekte fyrede gasturbiner (IFGT) er begrænset af den maksimalt opnåelige temperatur i processen, hvilken bestemmes af varmeveksleren mellem forbrændingsprodukter og luft til turbinen. Denne er begrænset og den opnåelige virkningsgrad for den simple IFGT er derfor ikke imponerende, men under det foreliggende projekts forløb har man fundet frem til to nye proceskonfigurationer for IFGT. De teoretiske studier viser at disse vil kunne opnå en meget høj virkningsgrad for IFGT-processen sammenlignet med de nuværende kommercielle alternativer.

Den ene konfiguration, *Våd IFGT*, kombinerer en IFGT med en brændselstørre-enhed, hvorved man vil kunne anvende biomasse med op til 85% vand, altså slam. Herved opnås en virkningsgrad, som for nuværende, kommercielle mikroturbiner vil være over 40%. Dette skal sammenlignes med nuværende teknologi, biogasanlæg, for hvilke virkningsgraden er i størrelsesordenen 10%-15%.

Den anden konfiguration kombinerer ekstern fyring med intern tilsatsfyring af en gasturbine. Den interne fyring baseres på rent gasformigt brændsel, såsom naturgas eller produkter fra pyrolyse af biomasse. Med denne konfiguration vil man opnå en høj marginal virkningsgrad på den interne fyring og i tilfældet med pyrolyse, en høj virkningsgrad på biomassefyring af gasturbiner, da man ikke længere er begrænset af varmevekslerens maksimaltemperatur.

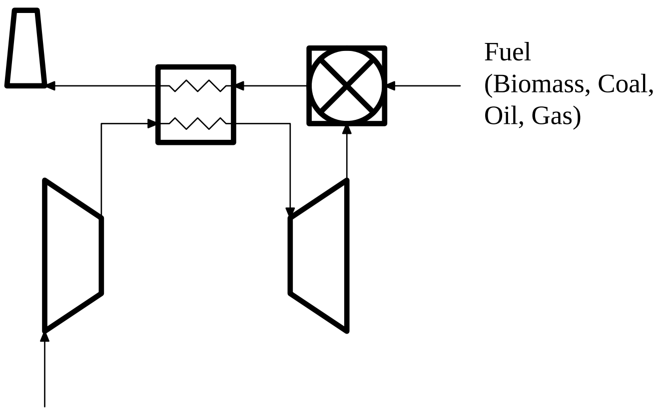
En mindre del af projektet har drejet sig om indhentning af oplysnionger om materialer og mulige konstruktioner af den mest kritiske komponent, varmeveksleren.

Indhold

Kapitel 1

Status for projektet

I det følgende slutrapporteres EFP-projektet, Projekt inden for procesintegration, på det nuværende Institut for Mekanik, Energi og Konstruktion[1] på Danmarks Tekniske Universitet.
Projektets hovedformål har været at udvikle systemer for anvendelse af gasturbiner i forbindelse med biomassebaseret kraft- og kraftvarmeproduktion. Fokus har været på *Indirekte Fyrede Gasturbiner (IFGT)*, en teknologi som endnu ikke har nået det fornødne niveau til at realiseres kommercielt. Et diagram for en IFGT ses i figur 1.1.



Figur 1.1: Skematisk diagram for Indirekte Fyret Gasturbine

Projektets resultater er beskrevet i tre papers. Et blev præsenteret ved konferencen ECOS 2001, [18], medens de to øvrige [17, 16] er fremsendt til review ved henholdsvis ECOS 2002, Berlin, og ASME IGTI Turbo Expo 2002, Amsterdam. Der foreligger desuden en intern rapport, [21], og et an-

[1]Tidligere: Institut for Energiteknik

tal arbejdsnotater som er udarbejdet i løbet af projektet. Udviklingen af processen „Våd IFGT“, se kapitel 3, var under overvejelse for patentering af DTU, men blev ikke patenteret, da arbejdet desværre allerede var blevet offentligt præsenteret. Projektets beregningsmæssige behov har nødvendiggjort en videreudvikling af modeller for komponenter og systemer for den indirekte fyrede gasturbine for anvendelse i simuleringsprogrammerne DNA og EES. Samtidig er der foretaget videreudvikling af selve simuleringsprogrammet DNA og enkelte andre softwareudviklinger. DNA er tilgængeligt som „open source“ via internet `http://www.et.dtu.dk/software/dna`.

To specialkurser [11, 22] er afsluttet af studerende, mens et tredje vil blive færdiggjort i februar 2002. I alt ni studerende har deltaget i disse kurser. To eksamensprojekter er i gang. Disse vil blive færdiggjort hhv. ultimo april og ultimo november 2002. Flere af disse studerende har leveret væsentlige bidrag til idegrundlaget for de nye processer.

En mindre del af projektets ressourcer er blevet anvendt i samarbejde med et andet, beslægtet projekt vedrørende opskalering af den DTU-udviklede totrinsforgasser til fluidbedanlæg, da denne repræsenterer et alternativ for produktion af „ren“ gas. Dette samarbejde er udmundet i publikation af et paper [7] samt to posters ved internationale konferencer.

Projektet er foregået i nært samarbejde med de projekter, der foregår omkring halmforgasning og biomassefyrede Stirling-motorer på Institut for Mekanik, Energi og Konstruktion. Disse projekter fokuserer i højere grad på anden konverteringsteknologi (forbrændings- og Stirling-motorer) og gasturbinestudier er derfor et vigtigt supplement til disse.

I rapporten fokuseres der primært på forskningen omkring kernen af arbejdet, altså „indirekte fyrede gasturbiner“.

1.1 Publikationsliste

Udover nærværende rapport er følgende publikationer er udarbejdet under projektet

1.1.1 Refereed papers ved internationale konferencer

- Brian Elmegaard and Bjørn Qvale
  Analysis of indirectly fired gas turbine for wet biomass fuels based on commercial micro gas turbine data.
  Præsenteres ved ASME IGTI Turbo Expo 2002, Amsterdam, Juni 2002.

- Brian Elmegaard and Bjørn Qvale
  Thermodynamic analysis of cofiring of gas turbine cycles.
  Fremsendt til ECOS 2002, Berlin, Juli 2002.

- Brian Elmegaard, Bjørn Qvale, Giacinto Carapelli, and Pietro de Faveri Tron.
  Open-cycle indirectly fired gas turbine for wet biomass fuels.
  I *Proceedings for ECOS '01*, Istanbul, pages 361–368, 2001.

- Jens Dall Bendtsen, Reto M. Hummelshøj, Brian Elmegaard, and Ulrik Henriksen.
  Low tar and high efficient gasification concept. I *ECOS 2000 Proceedings, Additional Papers*, Universiteit Twente, Holland, 2000.

1.1.2 Specialkursusrapporter

- Pietro de Faveri Tron and Giacinto Carapelli.
  Analysis of an ifgt (indirectly fired gas turbine).
  Institut for Energiteknik, DTU, 2000

- Nicola Gelli, Giovanni Sarti, and Marco Donati. *Biomass fuelled power plants.*
  Institut for Energiteknik, DTU, 2000

1.1.3 Software

Hjemmeside for DNA: `http://www.et.dtu.dk/software/dna` med manual og tutorial: Brian Elmegaard, *„The Engineer's DNA by Example"*, Technical University of Denmark, Department of Energy Engineering, 2000.

1.2 Motivation

Projektet har to indgangsvinkler, som begge begrunder studiet af indirekte biomassefyring af mikrogasturbiner.

- Biomasse anvendes nu i mange sammenhænge til elproduktion. Specielt har dampkraftværker taget biomasse ind som et brændsel på lige fod med kul, olie og naturgas. Den store udfordring i anvendelsen af biomasse og i energisektoren generelt er på nuværende tidspunkt at overgå til distribueret produktion på små anlæg helt ned til enfamiliehusstørrelse. Et sådant anlæg kan ikke i dag baseres på dampkraft.

- Konventionelle gasturbiner er af hensyn til korrosionsproblemer i turbinen og forbrændingsstabilitet bundet til drift på naturgas eller anden gas/olie med samme høje brændværdi. Derfor er deres anvendelse ikke et alternativ for biomassebaserede værker. Der er blevet gjort store anstrengelser for at øge deres anvendelighed i forbindelse med biomasse. Dette har dog primært sigtet mod at udvikle evnen til at anvende gas med lav brændværdi, som den der produceres ved forgasning af kul og biomasse samt „lossepladsgas". Der findes i dag gasturbiner til dette formål. Anvendelsen af disse rettes mod integrerede forgasnings- og combined cycle-anlæg; altså anlæg med både forgasning, gasturbine og dampturbine med afgaskedel. Denne konfiguration er kompliceret og kan ikke anvendes for små anlæg. Uden afgaskedlen vil energiudnyttelsen for disse gasturbiner være lav. Af den grund er de nye rekupererede mikrogasturbiner, som yder en lav effekt ved en høj virkningsgrad, interessante, da de er født med rekuperator og derved arbejder optimalt ved lave trykforhold. Udvikling af disse har krævet betydelig indsats over de sidste 40 år, men det er først i løbet af de sidste par år at de er blevet markedsført. Med deres tilstedeværelse på markedet er det blevet overmåde interessant at undersøge mulighederne for anvendelse i sammenhæng med biomasse baseret på ekstern fyring og varmeveksling i stedet for forgasning og direkte fyring.

På Institut for Mekanik, Energi og Konstruktion har man gennem en årrække arbejdet med at udvikle kraftproducerende processer og anlæg i lille skala baseret på hhv. stirlingmotoren og forbrændingsmotorer baseret på forgasningsgas. Begge projekter har resulteret i store fremskridt, og det er naturligt at et projekt som det foreliggende delvist er blevet baseret på den viden som allerede eksisterer i disse to projekter. Stirling-motoren opererer med en højtemperaturvarmeveksler, mens forgasning er en mulighed for konvertering af brændslet inden forbrænding for derigennem at højne virkningsgraden (ved luftforvarmning). Studier af en indirekte fyret gasturbine kompletterer instituttets forskning inden for biomasseområdet ved at inddrage en konverteringsteknologi, som vil have andre fordele og ulemper end de allerede undersøgte. Et par fordele ved den indirekte fyrede gasturbine er

- at den teoretisk vil have en høj maksimal virkningsgrad

- at der ikke kræves konvertering til gas for at anvende biomasse, men det vises at i nogle tilfælde kan pyrolysering og forgasning være fordelagtigt

- at den i ren eldrift ikke vil være afhængig af et eksternt vandbaseret kølesystem, samt
- at luften til forbrændingen vil være forvarmet til en høj temperatur, hvorfor der arbejdes med et stort luftoverskudstal og heraf følgende lavt indhold af korrosive stoffer i røggassen.

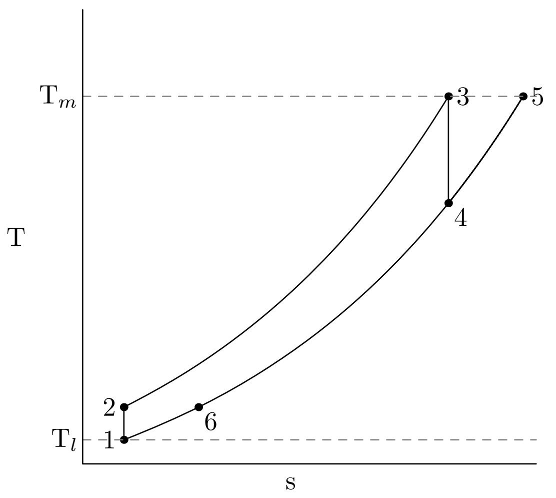
1.3 Denne rapport

Rapporten er bygget op med grundlæggende betragtningner omkring den indirekte fyrede gasturbine og de problemer, der er med dens konstruktion. Dette beskrives i næste kapitel. Herefter følger to kapitler, som kort beskriver de to proceskonfigurationer, som er udviklet under projektet. Den våde IFGT beskrives i kapitel 3, mens IFGT med tilsatsfyring er beskrevet i kapitel 4. Kapitlerne suppleres med de udarbejdede papers, som findes i bilag. Slutteligt indeholder rapporten en beskrivelse af arbejdet med varmevekslerkonstruktion samt en konklusion.

Kapitel 2

Grundlæggende betragtninger og forudgående arbejder

Arbejdet med at udvikle gasturbiner til ekstern fyring daterer sig langt tilbage [5, 38], men har aldrig rigtig slået igennem som en vigtig teknologi i kraftværksbranchen. Dette har primært teknologiske årsager, da den mest vitale komponent i processen, varmeveksleren, (se figur 1.1) overfører varme fra den eksterne forbrænding til den tryksatte luft før indløb til turbinens ekspansionsdel. Derved vil den være begrænsende for den opnåelige virkningsgrad for processen. Denne komponent er central, da materialet i den vil være bestemmende for den maksimalt opnåelige temperatur i kredsprocessen, som ses i figur 2.1 for idealiserede processer.



Figur 2.1: T-s–diagram for IFGT

Ideelt set vil enhver proces være begrænset af Carnotvirkningsgraden,

η_{carnot} (ligning (2.1)), som er omvendt proportional med processens maksimale temperatur.

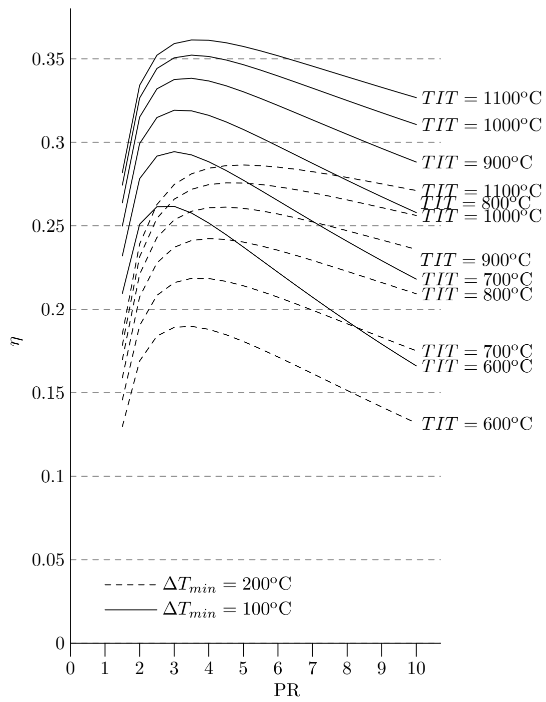
$$\eta_{carnot} = 1 - \frac{T_0}{T_{max}} \tag{2.1}$$

hvor T_0 er omgivelsestemperaturen og T_{max} processens maksimale temperatur.
En IFGT svarer termodynamisk set til en rekupereret gasturbine, som kun i specialtilfældet med trykforhold, $PR = 1$, vil have en virkningsgrad som Carnotprocessen. Virkningsgraden, η_{th}, for en ideel IFGT er:

$$\eta_{th} = 1 - \frac{T_2}{T_3} = 1 - \left(\frac{p_3}{p_1}\right)^{\frac{\kappa-1}{\kappa}} \cdot \frac{T_1}{T_3} \tag{2.2}$$

hvor κ er isentropeksponenten og de enkelte tilstande for tryk, p, og temperatur, T fremgår af figur 2.1.
Af begge udtryk for virkningsgraden ses at turbineindløbstemperaturen, TIT, vil være begrænsende for virkningsgraden. Det er derfor af største vigtighed at opnå en så høj temperatur som muligt i varmeveksleren.
Imidlertid har flere udviklingsstudier vist at denne temperatur ikke umiddelbart kan hæves til et niveau som kan resultere i acceptabelt høje virkningsgrader [8, 20, 23, 27, 28, 29, 32, 35]. For det første vil varmevekslere af metalliske materialer være begrænset med hensyn til styrke og korrosion hvis materialetemperaturen overstiger 700–800°C. Over denne temperatur må man formentlig ty til keramiske materialer, for hvilke konstruktionsmæssige problemer endnu ikke er løst. Det bør også anføres at de eksisterende keramiske varmevekslere er alt for dyre for de foreliggende anlæg. Det arbejde der er udført omkring varmevekslere i løbet af projektet uddybes i kapitel 5.
Med denne af nuværende teknologiske stadium fastlagte begrænsning på systemet er den opnåelige virkningsgrad for en IFGT relativt begrænset sammenlignet med andre typer af systemer. I instituttets to tidligste studier af emnet, [26, 30], har det også vist sig at en IFGT uden modifikationer, *en simpel IFGT*, ikke kan opnå virkningsgrader, der kan konkurrere med anden og fungerende teknologi. Denne observation er bekræftet af det nærværende projekt, hvilket både er beskrevet i [18] og [21]. Virkningsgraden for den simple IFGT-proces fremgår af figur 2.2 for forskellige turbineindløbstemperaturer og brændsel med 50% fugt, svarende til træflis. Med en turbineindløbstemperatur, TIT, på 600°C, som modsvarer en forbrændingstemperatur omkring 700°C, som vil være opnåelig med nuværende materialer vil virkningsgraden ligge på omkring 26%. Det skal

derudover tages i betragtning at tryktab i varmeveksler og forbrændingsrummet er negligerede i modellen. Disse har en betydelig indflydelse, da turbinen har et lavt optimalt trykforhold omkring 3. Heraf ses at det ikke med nuværende materialeteknologi er muligt at opnå en tilstrækkeligt høj virkningsgrad for den simple IFGT.



Figur 2.2: Virkningsgrad for en simpel IFGT

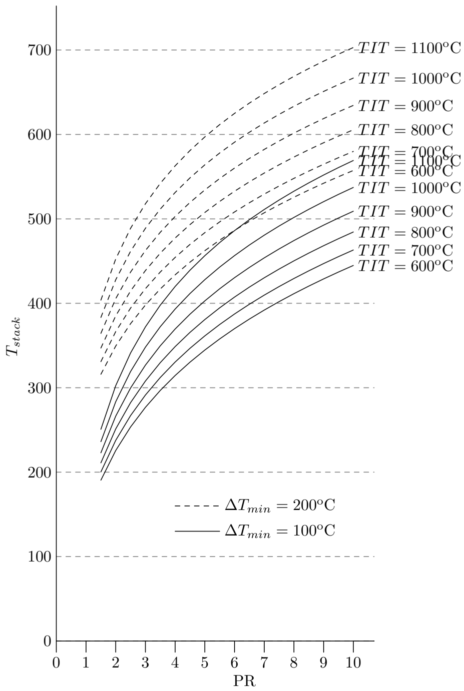
Det har medført at vi har fokuseret på at udvikle selve processen, således at den ikke vil være så udpræget begrænset af maksimaltemperaturen. Andre studier af gasturbiner i forbindelse med faste brændsler, biomasse såvel som kul, viser samme tendens. En høj elvirkningsgrad er ikke opnået i nogen af studierne [1, 3, 4, 14, 19, 31, 33, 34, 35, 36].
Det har derfor været nødvendigt at søge andre optimeringsmetoder for at opnå forbedringer af IFGT'en. Ved at se på hele anlægget og ikke IFGT-processen isoleret har vi fundet frem til to meget lovende proceskonfigurationer, som vil kunne anvendes for at opnå tilfredsstillende virkningsgrader ved anvendelse af biomasse til drift af gasturbiner i lille skala.

Kapitel 3

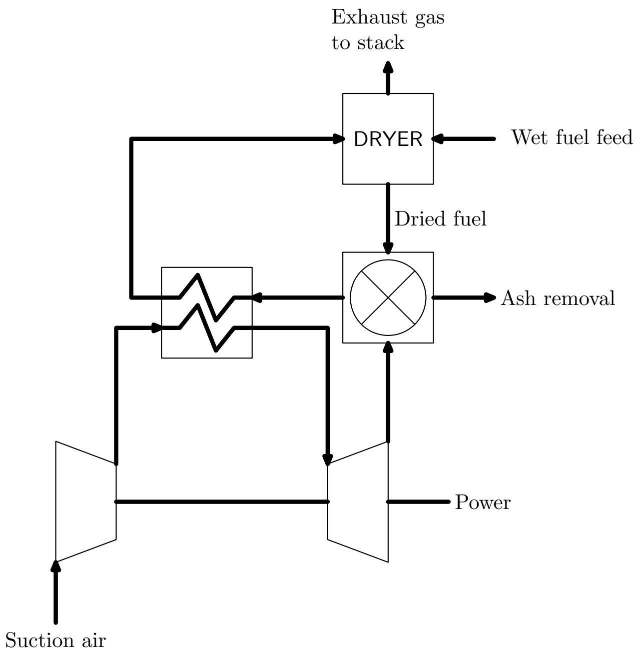
Procesudvikling: Våd IFGT

I studier af IGCC baseret på våde brændsler som træflis og brunkul er tørring med røggasserne efter køling i afgaskedlen en ofte anvendt metode for øge procesvirkningsgraden [2, 7, 9, 10, 13, 15, 24, 25, 37]. Da der i røggasserne fra indirekte fyrede gasturbiner vil være en del varme til rådighed har det været naturligt at undersøge muligheden for at anvende disse til tørring af brændslet på samme vis. Temperaturen af røggasserne ud af varmeveksleren fremgår af figur 3.1. Det ses at for en turbineindløbstemperatur på 600°C vil der for det optimale trykforhold være en temperatur over 250°C i røggasserne, og der er derfor basis for at indsætte en tørreenhed.
Tørreenheden indsættes som illustreret i figur 3.2. Beregninger viser at der med denne systemkonfiguration rent faktisk er mulighed for at anvende endog meget våde brændsler. Dette fremgår af figurerne 3.3 og 3.4. Det ses at virkningsgraden for en våd IFGT ved brændsel med kun 20% tørstof bliver 50%.
Disse beregninger viser at den våde IFGT kan konkurrere i virkningsgrad, hvis den anvendes til meget fugtigt brændsel, såsom kloakslam, gylle og industrispildevand. Disse typer af affald bliver for nuværende i nogen grad anvendt til energiproduktion baseret på biogas. Disse anlægs virkningsgrad er omkring 10-15%, altså opnår man med en våd IFGT en forbedring på flere hundrede procent i el-virkningsgrad.

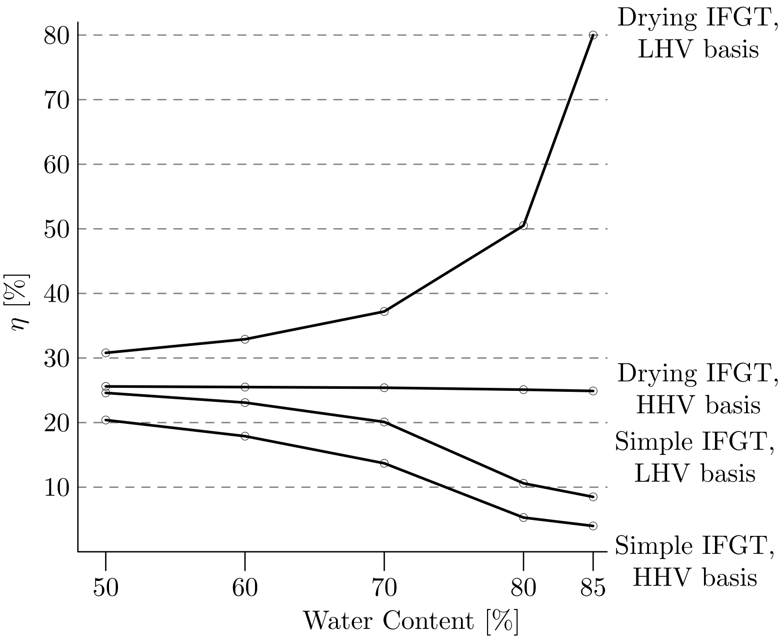
Delkonklusion Vi mener at med det med dette studium er vist, for det første, at en indirekte fyret gasturbine kan være kommericelt interessant, samt at den som „Våd IFGT“ rent faktisk vil kunne supplere det eksisterende udvalg biomassebaserede energiprocesser. Det er derfor vores håb i samarbejde med industrielle partnere at kunne demonstrere processen.



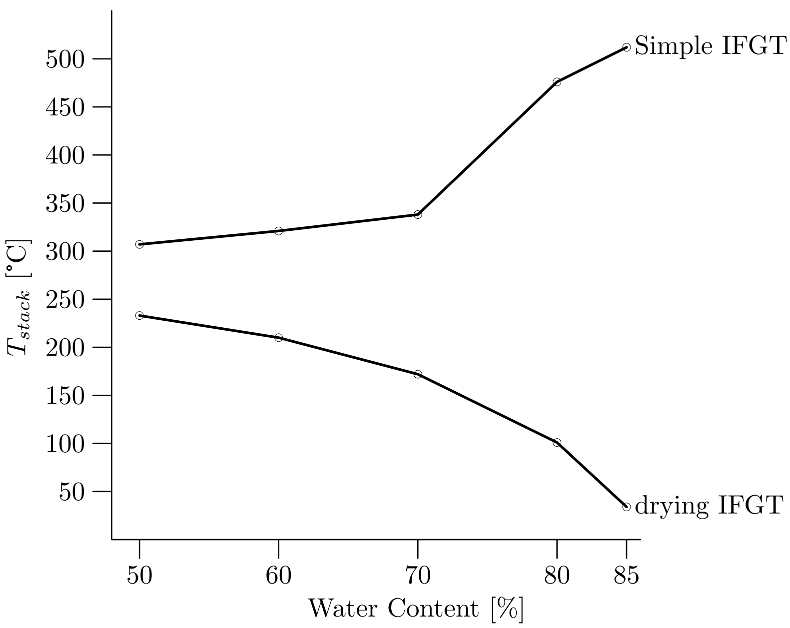
Figur 3.1: Skorstenstemperatur for simpel IFGT



Figur 3.2: Skematisk diagram for Våd IFGT



Figur 3.3: Virkningsgrad for simpel og våd IFGT baseret på antagede komponenteffektiviteter og negligering af tryktab



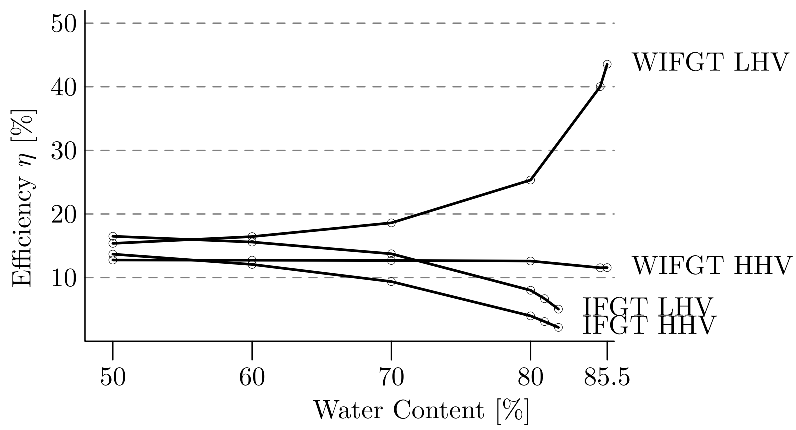
Figur 3.4: Udløbstemperatur for simpel og våd IFGT baseret på antagede komponenteffektiviteter og negligering af tryktab

Dette studium blev præsenteret ved konferencen ECOS '01. Paperet kan ses i bilag A.

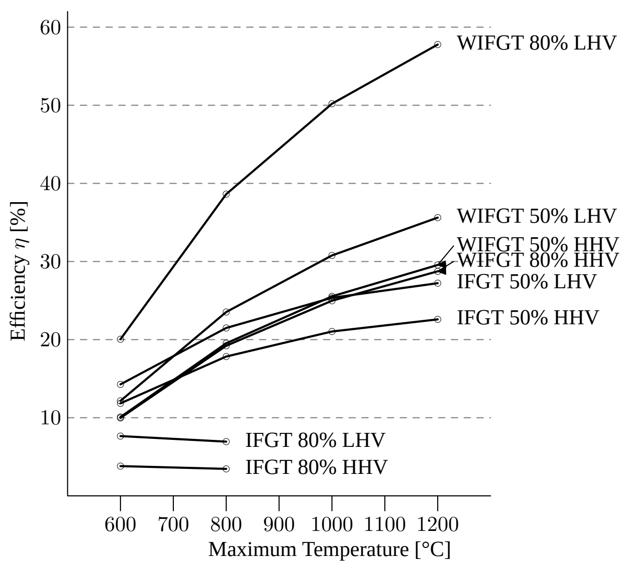
3.1 Model baseret på kommerciel mikrogasturbine

Grundet de lovende resultater for den våde IFGT er vi meget interesserede i at demonstrere konceptet. Af den årsag har vi været involveret i udveksling af information med forventning om senere at indgå i konkret samarbejde med den svenske mikroturbineproducent Turbec, som er interesseret i, med tiden, at indgå i et konkret samarbejde om udvikling af biomassefyret IFGT. Mikroturbiner er relativt nye i kommerciel sammenhæng, men der er for nuværende 5-6 producenter på markedet [12]. Disse har en nominel eleffekt på 30-100 kW. Turbecs maskine T100 har en ydelse på 100 kW.
Turbec har stillet data for en typisk mikrogasturbine til rådighed for et studium af den våde IFGT. Resultaterne af dette studium er at en våd IFGT af første generation ikke vil opnå de meget høje virkningsgrader som blev fundet for den idealiserede model beskrevet ovenfor. Dog er virkningsgraden for fugtigt brændsel omkring 40% hvilket stadig er cirka fire gange mere end der opnås på biogasanlæg. Samtidig giver den lavere virkningsgrad og mindre effektive udnyttelse af energien et større energiindhold i røggasserne, hvilket betyder at den maksimale fugtighed af brændslet kan være højere end for en idealiseret proces. Det betyder at brændsler med fugtindhold helt op til 85,5% vil kunne anvendes i en våd IFGT. Det tilsvarende minimale tørstofindhold på 14,5% er så lavt at mange slamtyper vil kunne anvendes i maskinen. Virkningsgraden for en våd IFGT baseret på Turbecs data fremgår af figur 3.5 og 3.6.

Delkonklusion Den foreløbige konklusion på arbejdet med „Våd IFGT" er at der for nuværende, reelt kommercialiserede mikroturbiner vil kunne opnås en virkningsgrad som overstiger det der opnås med nuværende slam-bioforgasningsanlæg med 3-4 gange og at der med udvikling af nye materialer for varmeveksleren vil kunne opnås endnu større virkningsgrader.
Dette studium vil blive præsenteret ved konferencen ASME IGTI Turbo Expo 2002. Paperet kan ses i bilag B.



Figur 3.5: Virkningsgrad ved forskelligt fugtindhold i brændsel for våd IFGT baseret på typiske mikroturbinedata

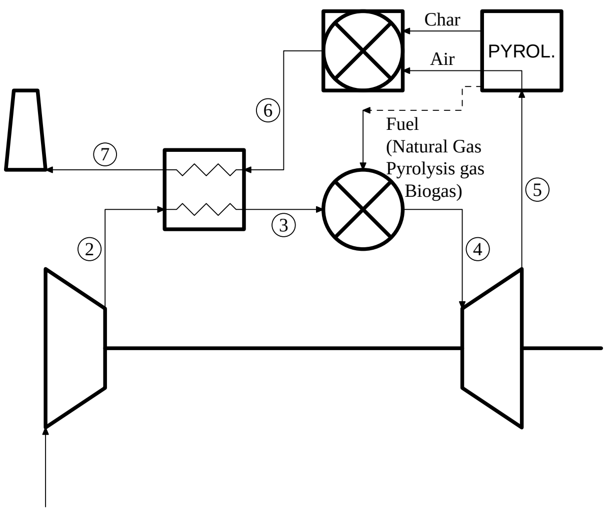


Figur 3.6: Virkningsgrad ved forskellig maksimaltemperatur for våd IFGT baseret på typiske mikroturbinedata

Kapitel 4

Procesudvikling: Gasturbine med ekstern fyring og intern tilsatsfyring

Da det største problem med den indirekte fyrede gasturbine er temperaturbegrænsningen i varmeveksleren har vi forsøgt at omgå denne begrænsning ved at tilsatsfyre med en ren gas, som gasturbinen vil kunne tåle internt uden korrosionsproblemer. Derved kan man opnå en høj forbrændings- og turbineindløbstemperatur og en heraf følgende højere virkningsgrad. Et skematisk diagram for denne proceskofiguration ses i



Figur 4.1: Skematisk diagram for IFGT med intern tilsatsfyring

Rent teknologisk kan man tænke sig to muligheder for at få en ren gas til rådighed for tilsatsfyring ved biomassebaserede IFGT-anvendelser.

Integration med pyrolyse Ved at pyrolysere biomassen vil en del af den (op til ca. halvdelen af brændværdien) blive omsat til en gas. Denne kan anvendes for intern forbrænding, mens den resterende koks kan afbrændes ved lavere temperatur eksternt, hvorved svovl og klor kan tilbageholdes. Dette betyder at man for biomassen opnår en højere maksimaltemperatur i processen og derved får et øget virkningsgradspotentiale.

Naturgas Naturgas eller tilsvarende ren gas/olie er det almindeligt anvendte brændsel i gasturbiner. Ved først at udføre opvarmningen med biomasse fra ekstern fyring og derefter anvende naturgas internt har det været antaget at man ville opnå en højere marginalvirkningsgrad på naturgassen[38], idet det er hvad man opnår med en rekupereret gasturbine. Det er derfor interessant at vores beregninger viser at dette ikke er tilfældet. Faktisk vil man ikke få højere virkningsgrad end man opnår i en rekupereret gasturbine. Marginalvirkningsgraden er endog uafhængig af turbineindløbstemperaturen. Hvis naturgassen skal opnå en høj marginalvirkningsgrad vil det kræve at man definerer elproduktionen uforholdsmæssigt mellem biomasse og naturgas. Dette vil være en ukonventionel definition og er derfor ikke taget med i vores hidtidige betragtninger.

Som proces betragtet vil denne konfiguration naturligvis stadig opnå en højere virkningsgrad end en simpel IFGT, da den maksimale forbrændingstemperatur er højere.

Delkonklusion Det er vist at ved at anvende intern tilsatsfyring i en IFGT kan man opnå en række teknologiske fordele, bl. a. opkontrering af korrosive kemiske forbindelser i koks eller askerest, hvorefter de så kan viderebehandles uden at skade turbine og/eller højtemeperaturvarmeveksler. Det bliver også muligt at hæve den totale virkningsgrad betydeligt.
De foreliggende studier viser imidlertid at den marginale (modsat den totale) virkningsgrad for naturgasbrændsel, modsat forventningerne, vil være lavere end den maksimale virkningsgrad, der kan opnås i en rekupereret gasturbine.
Dette studium vil blive præsenteret ved konferencen ECOS 2002. Paperet kan ses i bilag C.

Kapitel 5

Varmevekslere

Da den kritiske komponent i processen er varmeveksleren er det af stor betydning at konstruere denne så den vil fungere optimalt i en IFGT. Konstruktion af veksleren indebærer både valg af materiale og optimalt design. For nuværende er der udelukkende foretaget indledende undersøgelser af erfaringer med de forventede forbrændingsprodukterne og af de materialer, som er tilgængelige på markedet.
En foreløbig konklusion er at hvis varmeveksleren skal bygges af metallisk materiale vil den maksimale procestemperatur være begrænset til 700-800°C. Hvis man ønsker at operere over denne temperatur vil keramiske materialer være nødvendige i varmevekslerkonstruktionen.

Kapitel 6

Konklusion og fremtidigt arbejde

6.1 Konklusion

Med en utraditionel tilgang til problemet med at opnå en acceptabel/høj virkningsgrad for en IFGT baseret på biobrændsel har vi i projektet vist at denne type proces har potentiale for at blive et alternativ til andre kraftvarmeanlæg og at den vil kunne indgå i industriellen processer. Vi har fundet at de to nye proceskonfigurationer, *Våd IFGT* for slam og andet vådt brændsel samt *IFGT med intern tilsatsfyring* med henblik på høj virkningsgrad vil være yderst interessante for fremtidige procesanlæg både ud fra et energiproduktionshensyn og på grund af miljømæssige fordele.

Våd IFGT er interessant primært af to årsager:

- Processen kan arbejde med meget fugtig biomasse som slam og gylle og vil derved være et meget interessant alternativ til biogasanlæg, da den har en 3 til 10 gange så høj virkningsgrad. Eneste restprodukt fra den er aske, og ikke hele slamvolumenet, som i biogasanlæg.
- Samtidig er processen yderst velegnet til integration i industrielle procesanlæg, hvor der er behov for procesvarme.

IFGT med intern tilsatsfyring er også interessant, da den potentielt giver en langt højere virkningsgrad en den udelukkende indirekte fyrede turbine. Dette skyldes at temperaturen i den interne fyring kan være langt højere end for ekstern fyring. Processen vil ligeledes være meget fleksibel hvad brændsel angår, således at man kan anvende alle rene brændsler for intern fyring og alle andre eksternt. Gasturbinen er formentlig den eneste teknologi der har denne egenskab.

6.2 Fremtidigt arbejde

Der er ingen tvivl om at dette arbejde bør opfølges fremover.
For at nå fra nuværende niveau, hvor vi har etableret det termodynamiske fundament for IFGT's berettigelse til en turbine, som vil kunne vinde indpas i energiforsyningen er der flere studier, som bør foretages. Disse vil blive studeret fremover i forbindelse med studenterprojekter og yderligere forskningsprojekter.
Følgende vigtige aspekter bør undersøges:

Design af varmeveksler Varmevekslingen er som beskrevet et kardinalpunkt for en IFGT. Det er absolut nødvendigt at undersøge hvilke materialer der vil være bedst egnede til denne konstruktion samt hvordan den konstrueres og bedst integreres med forbrændings- og tørreenhed. Det primære fokus på småskalaanlæg betyder at der skal en billigst mulig konstruktion må findes.

Tørring For den våde IFGT er tørring af biomassen vigtig, og det vil blive studeret hvordan den bedst udformes med henblik på virkningsgrad, økonomi og miljø. specielt bør eventuelle lugtgener i omgivelserne minimeres.

Cases IFGT for småskalaelproduktion vil være yderst interessaqnt i forbindelse med industrielle anlæg og procesintegration, for eksempel i fødevare"- og papirindustri. Der vil af den årsag blive undersøgt hvilke industrier som kan have interesse i de nye proceskonfigurationer og hvordan økonomi og miljøforhold i disse vil være sammenlignet med alternativer.

Gasrensning Ikke bare for en IFGT integreret med pyrolyse/forgasning, men for biomasseanlæg i det hele taget er gasrensning ved høj temperatur, „hot gas cleanup", yderst interessant, da en sådan vil være med til at øge virkningsgraden af processen.

Grundet disse mangeartede vil det kommende arbejde med IFGT nødvendiggøre en yderligere involvering af industri og rådgivere, samt yderligere samarbejde med andre forskningsinstitutter på og uden for DTU.

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Bilag A

Paper præsenteret ved ECOS ’01

Open-cycle Indirectly Fired Gas Turbine for Wet Biomass Fuels*

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Abstract

The Open Cycle Indirectly Fired Gas Turbine (IFGT) allowsa wide range of fuels, solid, liquid or gaseous, to be used. The present study concerns the utilization of biomass fuels.

In an IFGT the exhaust from the turbine is used as combustion air. The internal combustion chamber is replaced by a heat exchanger heating the air from the compressor, thus eliminating the flow of flue gas through the turbine.

A wood fired IFGT was chosen as reference case. It was found that for this reference, only a low efficiency (below 30% for $TIT = 1100$°C) may be obtained. The main reasons for this is that the exhaust temperature to the stack is high and that the fuel has a high water content (50% on wet basis). This suggests that the performance could be improved, by adding a fuel dryer driven by the flue gas. This study shows that this does improve the efficiency of the cycle dramatically. However, the flue gas enthalpy still is not fully utilized.

This suggests that this system could be used for disposal of still cheaper waste fuels with even higher water content, such as sewer sludge. Calculations show that fuels with a water content of up to 80% may be used. At this point the efficiency on lower heating value basis increases to 50.5%. Equally interesting is, that the efficiency on higher heating value basis is close to 25% for all water contents of the fuel.

Nomenclature

η	Efficiency [–]
$\eta_{is,c}$	Compressor isentropic efficiency [–]
$\eta_{is,t}$	Turbine isentropic efficiency [–]
$HHV_{received}$	Net calorific value as received [MJ/kg]
λ	Excess-air ratio [–]
LHV_{dry}	Gross calorific value on dry basis [MJ/kg]
$LHV_{received}$	Gross calorific value as received [MJ/kg]
Δp_{tot}	Total pressure loss in cycle [bar]
PR	Pressure ratio [–]
ΔT_{min}	Minimum temperature difference in heat exchanger [°C]
τ	Temperature ratio [–]
T_{stack}	Stack temperature [°C]
TIT	Turbine inlet temperature [°C]
y_{Cl}	Volume fraction of chlorine [–]
y_S	Volume fraction of sulphur [–]

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1 Potential of the IFGT

The power generation field is dominated by conventional Rankine steam power plants. Such power plants

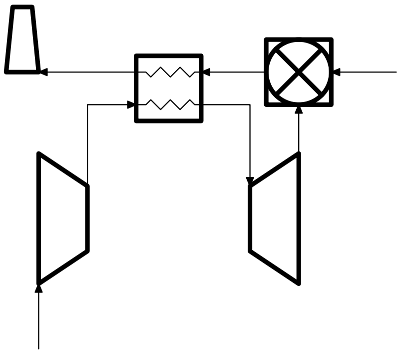

Figure 1: Simple-cycle IFGT

are usually quite big. At smaller sizes their efficiency fall and the costs rise.

Biomass is a resource that is spread out quite thinly, over geographically large areas. Transportation therefore is a potential problem. For this reason generation of power from biomass should preferably take place in decentralized power stations, that are smaller than what is usually considered economically and thermodynamically advantageous for the steam Rankine cycle. This is a power range in which the gas turbine becomes interesting.

However, a normal gas turbine cannot run on solid fuels. Therefore, the biomass will either have to be converted to gas through gasificationor utilized in an Indirectly Fired Gas Turbine. A schematic of a simple IFGT is shown in figure 1. The cycle is based on a gas turbine engine with compressor and expander, but with the combustion chamber replaced by a heat exchanger transferring heat from the combustion products to the compressed air from the compressor. The combustion takes place externally to the gas turbine and uses the turbine exhaust as combustion air.

In the present study, a modified IFGT process running on a range of biomass fuels with different water content has been studied. The process has been optimized using the simulator DNA[Elmegaard, 1999]. DNA is a flexible tool allowing parameter studies and process synthesis to be carried out easily. The models may easily be extended for part load and dynamic simulation.

2 Background

From the literature it appears, that the open-cycle indirectly or externally fired gas turbine, mainly has been studied as a process for utilizing coal in gas turbines. Biomass has mainly been considered as a fuel for conventional boilers and for IGCC's or gas engine plants, both requiring the fuel to be gasified[Beenackers, 1993, Obernberger, 1998]. The studies of the IFGT have focussed on the improvement of the cycle by construction of a heat exchanger applicable at very high temperature, above 1500°C. The studies have focussed on ceramic materials for construction of the heat exchanger or, alternatively, a regenerator[Pratt, 1999, Ferrato and Thonon, 1997, Solomon et al., 1996, LaHaye and Bary, 1994].

Other studies have focussed on the application of the IFGT in Combined Heat and Power Plants (CHP) [Edelmann and Stuhlmüller, 1997, Eidensten et al., 1996, Ruyck et al., 1994] for public utilities or in industrial applications using the heat for generation of steam or drying of raw material for industrial processes [Evans and Zaradic, 1996].

A considerable number of studies on closed-cycle externally fired gas turbines have been reported[Anheden and Ahlroth, 1997, Ahlroth, 2000].

3 Simple IFGT

The simple-cycle IFGT, as shown in figure 1, is a modified gas turbine, where the internal gas burner is replaced by an external combustion chamber and a heat exchanger. The fuel fed to the cycle is not limited to gaseous fuels, but may be liquid or solid as well. In the present study, we establish a reference case where the fuel is wood chips or wood waste.

The configuration is in the ideal case comparable to a recuperated gas turbine having the same advantages as this cycle.

The main advantages are low optimal pressure ratio and a maximum efficiency equal to the Carnot efficiency for an ideal process (in the limit when the pressure ratio approaches unity).

Obviously, it also has the same disadvantages as a conventional gas turbine. The main problem is that, in real cases, the temperature of the exhaust gases is quite high leading to considerable exergy loss and, consequently, a low thermal efficiency.

The efficiency of the cycle is closely related to the maximum allowable gas temperature, i.e., the combustion temperature, which in turn determines the turbine inlet temperature, TIT.

The reference case for the optimization study is calculations on a "simple-cycle" IFGT running on

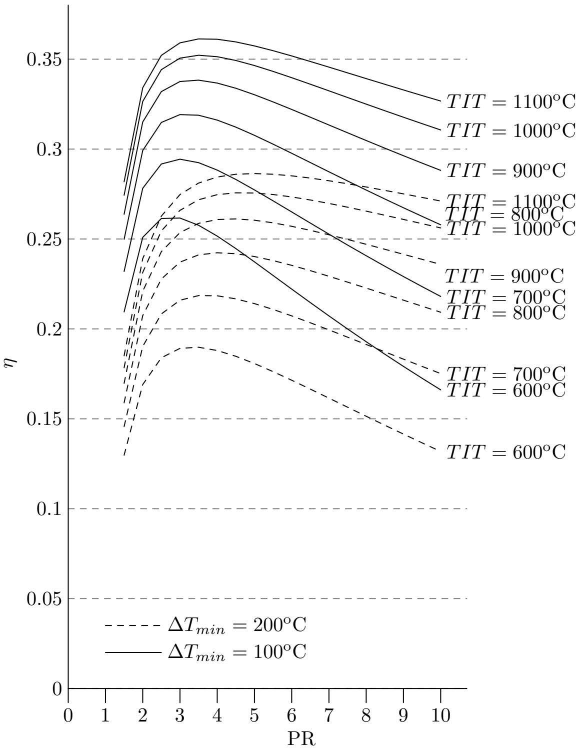

Figure 2: Efficiency of "Simple-Cycle" IFGT ($\eta_{is,c} = 0.9$, $\eta_{is,t} = 0.92$, $LHV_{dry} = 20.7$ MJ/kg)

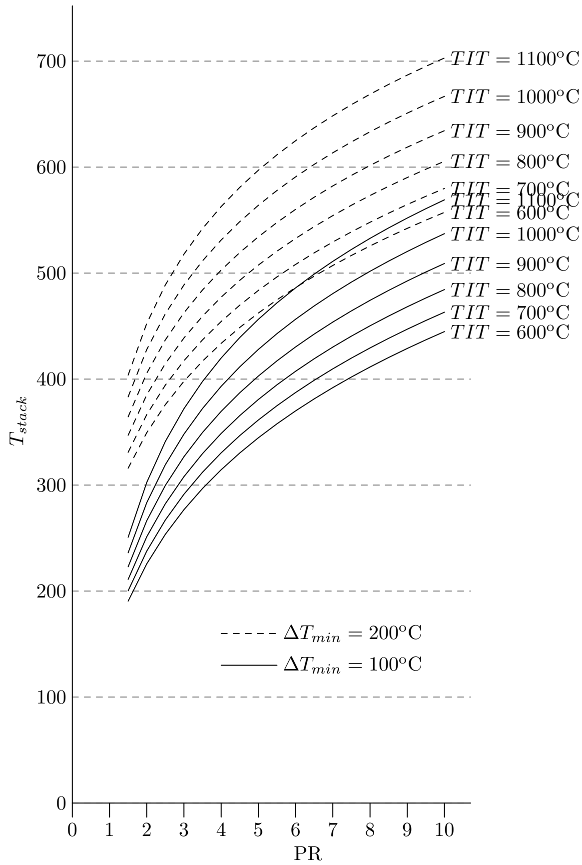

Figure 3: Stack temperature from "Simple-Cycle" IFGT

biomass. The graphs in figure 2 show the correlation between efficiency of the cycle and the combustion temperature for temperature ratios, τ, between 2.9 and 4.6. The calculations have been made for a minimum temperature difference of 100°C and 200°C in the heat exchanger. It is clear that the efficiency of the simple cycle is determined uniquely by the combustion temperature and the heat exchanger effectiveness. It is also seen that the efficiencies obtained are very modest even for very high combustion temperatures. The efficiency reaches only 29% for a TIT of 1100°C.

From figure 3 it is seen that the flue gases to the stack are very hot. That may be utilized in the search for an better process layout.

Another important limitation of the cycle is the heat exchanger transferring heat from the combustion products to the compressed air. As the combustion products are led directly from the combustion chamber to the heat exchanger, they will contain corrosives such as chlorine, sulphur and fly ash. Different technologies may be applied to clean the gases, but the selection of a suitable material for the heat exchanger is a major challenge. In this respect, an important parameter is the material temperature. The lower this may be selected, the easier it will be to find a suitable material. Several studies have focused on the use of ceramic materials, thus allowing the use of higher temperatures[Pratt, 1999, Kumada, 1999, Luzzatto et al., 1997, Solomon et al., 1996]. However, if the gas turbine is going to be based on current technology, metallic materials will have to be used, thus limiting the maximum allowable temperature.

In the present study the maximum allowable temperature in the heat exchanger walls has been set to 700°C. In figure 2 it is seen that the simple cycle for this combustion temperature, which is attainable with commercially available technology, and a minimum temperature difference of 100°C, corresponding to an effectiveness of 0.8, has a maximum efficiency of 18.6% at a pressure ratio $PR = 3.0$. This low efficiency would make the IFGT uninteresting in most situations.

4 The “Wet IFGT” – IFGT Combined with Fuel Drying

In order to improve the cycle efficiency, utilization of the flue gas enthalpy is the natural source of improvement. The fuel may be dried in order to avoid the evaporation and heating of the moisture concurrent with the combustion. It should be realized that without drying, the steam will remain in the combustion products, resulting in a higher mass and enthalpy flow, but this enthalpy cannot be utilized as the combustion products does not enter the turbine.

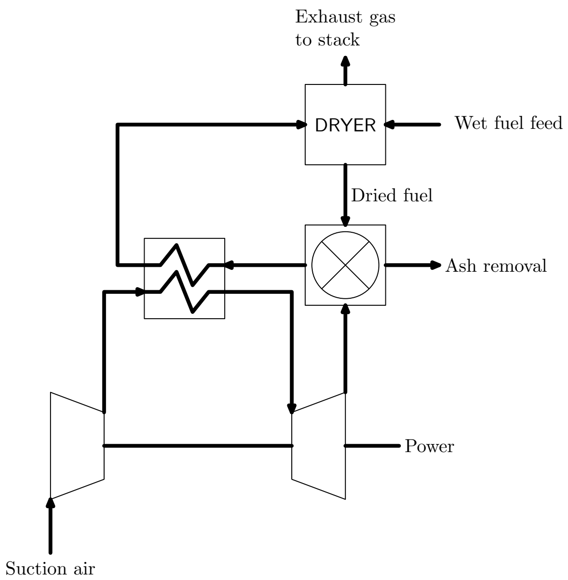

Figure 4: “Wet IFGT”

The flowsheet of a “Wet IFGT”, an IFGT with fuel drying is shown in figure 4. The wet fuel enters the dryer, where it is dried by the flue gas leaving the heat exchanger. The water in the fuel evaporates and is carried with the turbine exhaust to the stack. The dried fuel is led to the combustion chamber.

In the model it is assumed that the dried fuel and the flue gases, (including the evaporated water) leaving the dryer are at the same temperature. The heat exchanger effectiveness is 0.8, resulting in a turbine inlet temperature of 590°C with the combustion temperature of 700°C. Technically, biomass may be dried to around 10% moisture content.

The data that have been used for the wood chips are given in table 1, the cycle reaches an efficiency of 30.8% at a pressure ratio of 3.5. This may be compared

Carbon	59.00%
Hydrogen	6.00%
Oxygen	34.80%
Nitrogen	0.08%
Sulphur	0.04%
Ash	0.08%
Water content as received	50.0%
Lower Heating Value (LHV_{dry})	20.74 MJ/kg
Lower Heating Value ($LHV_{received}$)	11.02 MJ/kg
Higher Heating Value ($HHV_{received}$)	9.15 MJ/kg

Table 1: Data for Wood Chips (Percent by weight)

to the 24.6% obtained by the simple cycle. Thus, for wood chips the efficiency is raised by 24% by including the drying process. This result is very satisfactory, making the biomass-based IFGT competitive to other, more complex biomass cycles.

Furthermore, this result indicates that the use of the “wet IFGT” to even wetter fuels, such as sewer sludge, industrial waste and manure, all containing up to 85% water should be investigated. The results of a study of the IFGT working on fuels with a water content of up to 85% are shown in figure 5. Here it is seen that the efficiency of the cycle for very wet fuels is 80.0%. It is also seen that the efficiency based on higher heating value is constant and close to 25% for all water contents. This may be compared to the simple cycle running on wet fuel which has a net efficiency below 5% for the very wet fuels.

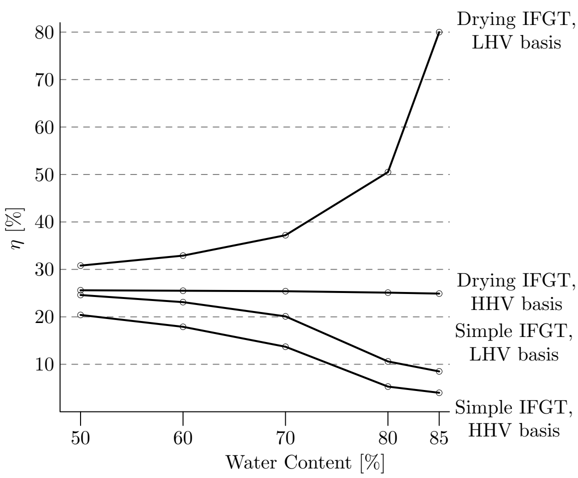

Figure 5: Net and Gross Efficiency of the Conventional and the “Wet IFGT” for Varying Fuel Water Content

However, as seen in figure 6, in this case, in which the combustion temperature is limited to 700°C, the stack temperature may be somewhat below 100°C, which may be inappropriate. Limiting the stack temperature to 100°C will require the moisture content of the fuel to be below 80%, at which the gross thermal efficiency is 50%. This still is a high efficiency for a power plant running on sewer sludge, and it may be raised by application of a higher combustion temperature. Higher combustion temperature will also raise the stack temperature for the wettest fuels. However, further studies show that a very high combustion temperature may be required. One way of keeping the stack temperature acceptably high, is to remove the water from the fuel to 75%–80% by mechanical means.

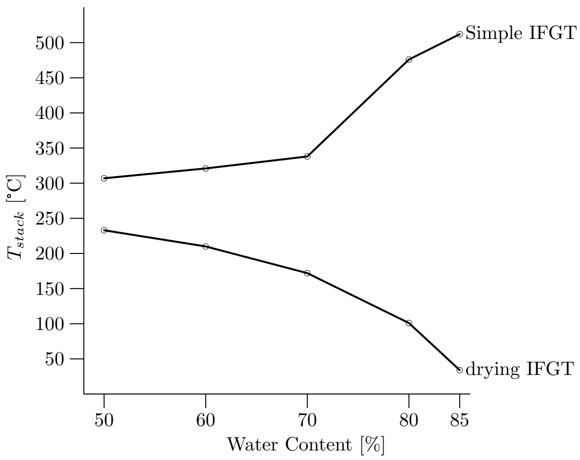

Figure 6: Stack Temperature of the Conventional and the "Wet IFGT" for Varying Moisture Content

5 Pressure Losses

Due to the low pressure ratio of the IFGT, the pressure losses in the process will have a considerable influence on the efficiency. This is illustrated in figure 7. The figure shows the efficiency of the cycle for both wood (50% water) and sludge/manure (80% water). For each of the two fuels the efficiency has been calculated for pressure losses assumed to be the same in each of the flow paths through passive components in the system (heat exchanger cold side, combustion chamber, heat exchanger warm side and dryer) and in the range of 0 to 0.4 bar in total.

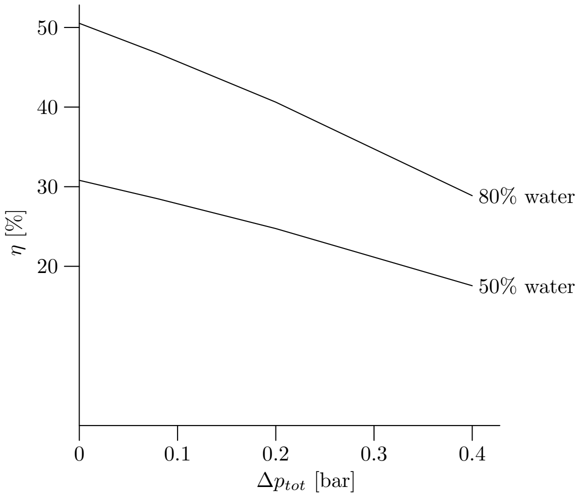

Figure 7: The Influence of Pressure Loss on Cycle Efficiency (LHV basis) for 50% and 80% Water Content in Fuel. (The pressure Loss, Δp_{tot}, is the total Pressure Loss in the cycle. The pressure losses in each of the Flows through Heat Exchanger Cold Side, Combustion, Heat Exchanger Hot Side and Dryer are equal.)

As expected pressure loss has a considerable influence on the efficiency of the cycle. This means that in an actual design of the components for the cycle an effort must be made to have as low pressure losses as possible.

6 Concerning Corrosives

The presence of corrosives in the flue gas is an important limitation to the cycle. It is therefore of importance to know the content of the aggressive gas compounds in the flue gas. Figure 8 shows the contents of the main corrosive compounds, chlorine and sulphur in the flue gases as a function of the excess-air ratio. The combustion, as carried out in the IFGT being considered, takes place at a high excess-air ratio. At the optimal pressure ratio of 3.5, the excess-air ratio, λ, is 7.0–7.2 for a water content of 50% to 80% in the fuel. In figure 8 it is seen that the amount of corrosives in the flue gas is very small, $\approx$ 25 ppm, for sulphur and almost vanishing for chlorine. These calculations are made with the assumption of wood (willow [Jenkins et al., 1998]) as a fuel and with the assumption of dry fuel. Sludges and waste streams may have a higher content of corrosives, but it is obvious that the

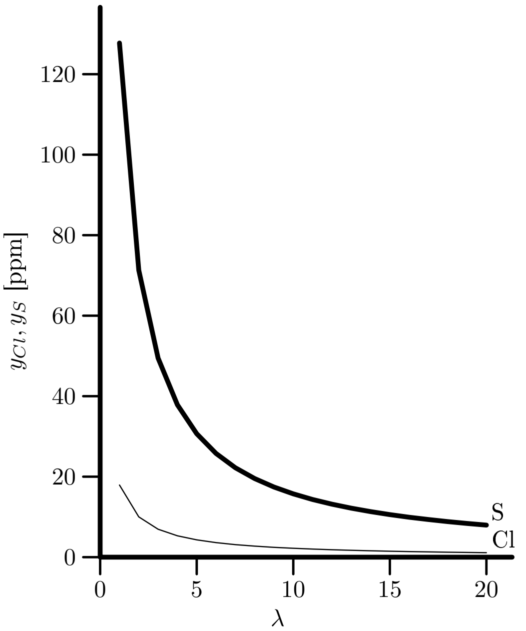

Figure 8: Contents of Sulphur and Chlorine in Flue Gas from Combustion of Dry Wood as a Function of Excess-air ratio

very high temperature of the combustion air coming from the expander allows the IFGT to be run at high excess-air ratio and thereby be less exposed to corrosives.

7 Perspectives and Further Work

This study has shown that the IFGT in which the exhaust gases are used for drying the fuel is very promising for application of wet biomass. The process may obtain well above 50% gross efficiency and has a constant net efficiency of 25% for the range of fuels considered in the present study. The stack temperature from the process is below 100°C for the highest moisture contents. For water contents less than 80%, no problems should be present, because the stack temperatures will be above 100°C. For higher water contents, mechanical water removal may be applied.

When the water content varies from 50% to 80% the stack temperature decreases from 250°C to 100°C. The enthalpy of this flow may be utilized for different purposes. These applications include

- production of process steam in industry
- heat for industrial processes, e.g., for drying of goods
- district or central heating

Many different fuels may be considered for the "wet IFGT". Along with the more conventional biomass, such as wood chips and wood waste, many different industrial wastes and sludges can be found, e.g., in food industry. In agriculture, manure is an interesting fuel, which is now being utilized in biogas plants with a rather low thermal efficiency. (Partly, because the treated manure is used as fertilizer.)

It is also of interest to consider the integration of the IFGT and biomass gasification. By gasification it may be possible to separate the clean and the dirty parts of the fuel, such that part of the gasification gas (syngas) may be burned inside the gas turbine combustion chamber. A related idea is to boost the IFGT by addition of natural gas in the combustion chamber. Both applications will lead to higher thermal efficiency of the cycle.

The ongoing development of micro and mini gas turbines with recuperation will make it easier to apply the IFGT in industry and agriculture, because the fuel flow is relatively small. The main challenge in the development of a commercially useful IFGT is the development of the heat exchanger and its integration with the combustion chamber, and potentially the drying.

8 Conclusion

The "Wet IFGT" has opened for the potential of having IFGT with acceptably high efficiencies with current-technology heat exchangers. Alternatively, the development of heat exchangers that are able to withstand the temperatures and corrosiveness of the combustion products will lead to very high efficiency of electric power generation from very low-quality, cheap fuels.

9 Acknowledgements

Danish Energy Agency and Nordic Energy Research Programme for Process Integration are acknowledged for financial support of the work.

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Bilag B

Paper til præsentation ved ASME IGTI 2002

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ASME TURBO EXPO LAND, SEA & AIR 2002
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ANALYSIS OF INDIRECTLY FIRED GAS TURBINE FOR WET BIOMASS FUELS BASED ON COMMERCIAL MICRO GAS TURBINE DATA

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ABSTRACT

The results of a study of a novel gas turbine configuration is being presented. In this power plant, an Indirectly Fired Gas Turbine (IFGT), is being fueled with very wet biomass. The exhaust gas is being used to dry the biomass, but instead of striving to recover as much as possible of the thermal energy, which has been the practice up to now, the low temperature exhaust gases after having served as drying agent, are lead out into the environment; a simple change of process integration that has a profound effect on the performance.

Four different cycles have been studied. These are the Simple IFGT fueled by dry biomass assuming negligible pressure loss in the heat exchanger and the combustion chamber, the IFGT fueled with wet biomass (Wet IFGT) assuming no pressure losses, and finally both the Simple and the Wet IFGT incorporating typical data for pressure losses of commercially available micro turbines.

The study shows that the novel configuration, in which an IFGT and a drying unit have been combined, has considerable merit, in that its performance exceeds that of the currently available methods converting wet biomass to electric power by a factor of five. The configuration also has clear advantages with respect to corrosion and to the environmental friendliness and the quantity of the waste products and their usefulness.

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Nomenclature

H_h	Higher Heating Value on wet basis [MJ/kg]
H_l	Lower Heating Value on wet basis [MJ/kg]
$\dot{m}_{fuel}$	Fuel mass flow [kg/s]
η_{HHV}	Efficiency based on higher heating value
η_{LHV}	Efficiency based on lower heating value
P	Net power production [MW]
TIT	Turbine Inlet Temperature [°C]
IFGT	Simple Indirectly Fired Gas Turbine
WIFGT	Wet Indirectly Fired Gas Turbine
HHV	Higher Heating Value
LHV	Lower Heating Value

INTRODUCTION

Motivation

The increased use of renewable energy is really the only lasting solution to the CO_2-problem and one of the most interesting challenges is the utilization of biomass for the production of electric energy. The present project is one amongst a number in this area of endeavor. Specifically, the aim of the project is to evaluate the potential of the gas turbine for generation of power from biomass. This can be done by gasification and gas cleaning, by solid-fuel combustion and filtering, or by external firing in an IFGT. This last alternative is the topic of the present investigation.

History

The Indirectly Fired Gas Turbine (IFGT) has been under consideration for a long time (Wilson, 1993; Most and Hagen, 1977). The driving force has almost exclusively been the possibility for using it for coal (Shenker et al., 1997; Solomon et al., 1996; LaHaye and Bary, 1994; Jahnig, 1986), but also wood has been considered. However, the big success has been absent. This is due to the limited durability of the heat exchanger material in the presence of corrosive gases, the problem of fouling, and also because of the very high efficiencies of the modern coal-fired steam power plants.

IFGT's have been the subject of many studies, but the resulting efficiencies have been quite low. The main optimization parameter has been the maximum temperature of the cycle which is that of the combustion products at the inlet of the heat exchanger. Moreover, many studies have focused on the IFGT for application to coal power (Leithner and Ehlers, 2000; Edelmann and Stuhlmüller, 1997; Solomon et al., 1996; LaHaye and Bary, 1994; Jahnig, 1986). One interesting reference on coal-fired IFGT's is the Ackeret-Keller-based plants, of which the oldest is the closed-cycle 2 MW plant, which has been in operation since the 1950's, operating with a maximum temperature of 700°C (Bammert et al., 1956). This is a low temperature for gas turbines in general and also for operation on coal, but it will be shown below that operating temperatures in this range may still be interesting for micro gas turbines fueled by wet biomass.

Open cycle Simple IFGT's for biomass does not appear to be better than coal cycles. They are both limited by the temperature. Also in the smaller sizes the high specific cost of high temperature heat exchangers rules out the use of these. It should be noted that one gas turbine has been modified for evaporative application (Ruyck et al., 1994) and others are under consideration mainly in research (Stevanovic, 2001; Evans and Zaradic, 1996; Eidensten et al., 1996).

Activities in the Field at the Technical University of Denmark

The reported study is one of a number of projects aimed at the utilization of biomass for generation of electric power. These include fundamental research, modeling and demonstration of gasification of wood and straw, cofiring of biomass with coal, biomass-fired Stirling engines, and biogasification of biomass. The activities in the area of the IFGT started in 1994 and have resulted in two Master Theses (Jørgensen, 1997; Olsen and Foldager, 1995) and a few informal reports, but a very modest rate of progress. However, quite recently, theoretical studies of a power plant design based on the combination of a biomass drying unit with the IFGT has shown results with considerable promise. Results to date point to an improvement of the conversion efficiencies relative to the best current competing technology, namely biogasification, with a factor of 4 to 10.

Thermodynamic aspects

The results of the present study appear quite peculiar with extremely high efficiencies compared to current gas turbine practice. This peculiarity hinge upon the composition of the fuels and upon the definition of efficiencies conventionally used in the field of biomass energy conversion.

The elemental composition of the fuels is as specified in table 1. The elements are given as weight percentages on dry basis and are based on data for wood, but they are representative for a large range of biomass fuels. The water content of biomass fuels may vary between some 20% for straw, over 40–50% for wood and other plants and to 80 to 95% for sludges and manure. This fact makes the biomass specific energy content and the difference between higher and lower heating value highly dependent on water content.

The efficiencies presented in the present paper are based on the conventional definitions of higher and lower heating value, respectively:

$$\eta_{LHV} = \frac{P}{\dot{m}_{fuel} H_l} \tag{1}$$

$$\eta_{HHV} = \frac{P}{\dot{m}_{fuel} H_h} \tag{2}$$

Today's common practice is to base the price of the fuel on the lower heating value of the wet fuel. In the present study this practice is extended to other very wet fuels, such as sludges.

Hydrogen	6.0	w-%
Oxygen	34.8	w-%
Nitrogen	0.08	w-%
Carbon	59.0	w-%
Sulphur	0.04	w-%
Ash	0.08	w-%
Specific Heat (dry base)	2.0	kJ/kgK
Lower Heating Value (dry base)	20740	kJ/kg
Moisture content (dry base)	50/80	%

TABLE 1. ELEMENTAL COMPOSITION OF DRY BIOMASS FUEL

Fuels

The Wet IFGT will be applicable to a wide range of fuels. The study in (Elmegaard et al., 2001) shows that even for low maximum cycle temperatures, the efficiency improvement by combining an IFGT with a drying unit will be advantageous, with the advantages being more significant for higher moisture contents. The limitation on the moisture content of the fuel is reached when the temperature of the gas in the stack falls below the dew point temperature.

In the present paper the composition of the biomass is as specified in table 1 unless otherwise stated.

Mathematical Model

The results shown in the paper are found by application of the open source simulation software DNA (short for Dynamic Network Analysis) available for download from `http://www.et.dtu.dk/software/dna`. The program is a component-based tool for steady state and dynamic simulation of power plant and other energy systems including gasification, combustion, fuel cells and so on.

Two particular features of DNA is that it calculates fuel and gas compositions as a part of the solution of the system of equations and that mass and energy balances are generated automatically, so they will always be satisfied for any component. Moreover, the component models will issue a warning for solutions to the mathematical model, which are not consistent with the physical conditions. One example in the Wet IFGT model is a check for the gas temperature being below the condensation temperature of the water vapor in it.

Parameters characterizing the separate components and the operation have been supplied by Turbec (Turbec AB, 2001). These parameters are shown in table 2 Turbec is manufacturer of the The T100 Micro Turbine. This machine is a 100 kW_{el} unit with a nominal electrical efficiency of 30% and a total efficiency in CHP mode of 80%. It is one of the five micro gas turbines currently available on the market (Dielmann, 2001).

THE PRESENT PROJECT

The performance of two different power cycles, the simple IFGT and the Wet IFGT, have been considered in two different situations, the one at close-to-ideal conditions without frictional flow losses in the heat exchanger and the combustion chamber and the other at conditions of a real, commercial micro turbine with frictional flow losses.

The Simple IFGT

The project is directed towards small decentralized power plants using small gas turbines of the size that currently is labeled micro turbines.

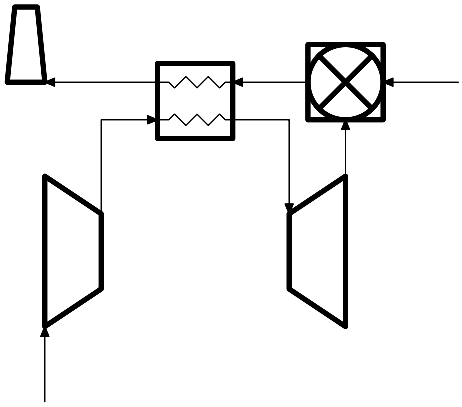

FIGURE 1. THE SIMPLE IFGT

The IFGT that is considered is, therefore, fundamentally very simple consisting of a compressor, a heat exchanger, a turbine and an atmospheric combustion chamber (see figure 1). There are no intercoolers or recuperators. It is quite clear that the cycle possess some basic weaknesses. The most obvious is that the amount of thermal energy that is added to the air in the combustion chamber and the thermal energy that leaves the heat exchanger both increase with the pressure ratio of the compressor, while the value of the turbine inlet temperature (TIT) is limited by the heat exchanger and not by the turbine, and therefore is quite low. The first studies (Jørgensen, 1997; Olsen and Foldager, 1995) therefore gave efficiencies in the lower twenties. Typical results are included in figure 3.

The Wet IFGT

In a recent paper (Elmegaard et al., 2001) the “Wet IFGT”, i.e., an indirectly fired gas turbine for wet biomass fuels (see figure 2) was presented. In this power plant an indirectly fired gas turbine cycle is integrated with a fuel drying unit. The fuel is heated and dried by the flue gases from the gas turbine. The drying unit is assumed to be a direct-contact heat exchanger where the water contained in the fuel evaporates into the hot flue gas. As the temperature of the flue gas does not exceed 200°C the biomass will not pyrolyse in this unit, and no loss of heating value in the drier has been considered. Therefore, the dry-fuel heating value is constant.

Even when subjected to current technology limitations imposed by the maximum allowable temperature of the material of the heat exchanger that is transferring heat between the combustion products and pressurized air, the results are very encouraging. For a turbine inlet temperature of 591°C (temperature ratio 2.5) and a fuel water content of 50%, it is found that with the Wet IFGT the efficiency for wood-fired IFGT’s is raised by 19%.

For biomass with higher moisture contents, such as sewage sludge, manure, and industrial wastes, the concept is even more

Parameter	Values in (Elmegaard et al., 2001)	Typical Micro Turbine Values (Turbec AB, 2001)
Temperature Ratio [-]	2.5	2.5 (Assumed value for IFGT)
Optimal Pressure Ratio [-]	3.0	3.5 (Calculated value for IFGT, TIT=591°C)
Turbine Inlet Temperature [°C]	591	591 (Assumed value for IFGT)
Compressor Isentropic Efficiency [-]	0.90	0.77
Turbine Isentropic Efficiency [-]	0.92	0.90
Heat Exchanger effectiveness [-]	0.80	0.88
Heat Exchanger Pressure Loss Hot side [°C]	0.0	0.1
Heat Exchanger Pressure Loss Cold side [°C]	0.0	0.1
Combustion chamber pressure ratio [–]	1.0	0.98
Outlet Moisture content from Dryer [%]	10	10
Drying unit Pressure loss [bar]	0.0	0.1

TABLE 2. PARAMETERS CHARACTERIZING THE COMPONENTS OF THE WET T MODEL CALCULATIONS SHOWN IN FIGURES 3 AND 4

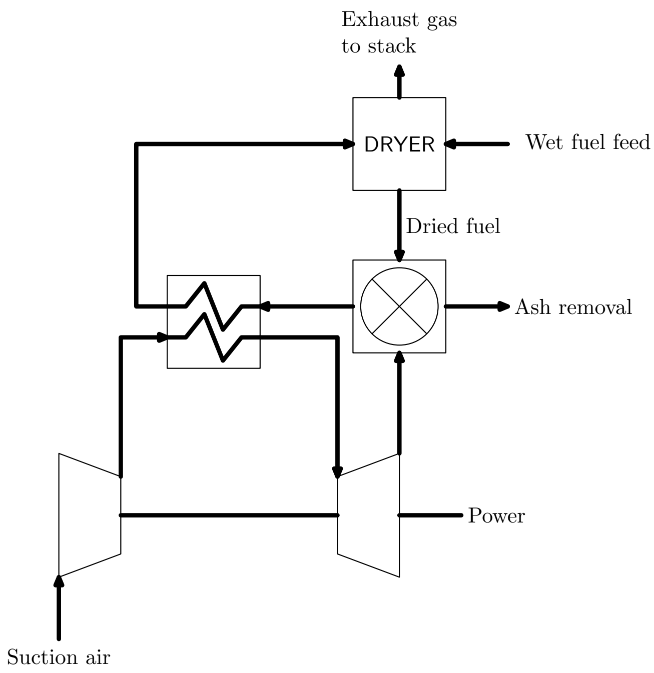

FIGURE 2. FLOWSHEET OF A WET IFGT

encouraging.

When used for power production, these wastes are presently converted in biogas plants through anaerobic digestion. This is a commercial technology. It is interesting both from an energy and from an agricultural viewpoint: It raises the fertility of the fuel, e.g., manure and it decreases odor problems. Moreover, the methane-rich gas can be utilized for power and heat production and thereby give supplemental income to the farmer. However, seen from an energy viewpoint biogas plants are not very efficient. On a power-to-fuel heating value basis, the efficiency is very modest, typically some 15% and 7% on lower and higher heating value, respectively. This is based on an assumption of 50% conversion of the manure and an engine efficiency of 30% (COWI A/S, 2002). Furthermore, the sludge volume is not changed in the process, requiring transportation to deposits on fields after the treatment. The Wet IFGT, therefore, may be very promising also from an economical viewpoint. The efficiency figures reported earlier (Elmegaard et al., 2001) are higher the higher the water content of the fuel, with a water content of 83% being the maximum possible amount. For such a fuel the efficiency of the Wet IFGT is 62.6%/24.9% based on lower and higher heating value, respectively. The results are reproduced in figure 3. Also, the amounts of solid and fluid rest products are much smaller than for current biogas technology. The only part left of the fuel will be ashes. The rest of the fuel is leaving by the stack after the combustion and the drying. As the digested sludge from biogasification, the ash may also have high fertilizing value, but is of much smaller volume.

Process Integration

The aim of the project is to explore and develop indirectly fired gas turbines systems for applications in small-scale biomass electricity production, possibly integrated in industrial processes. A number of micro gas turbines have recently been introduced on the market. In small scales the optimal system is a low pressure

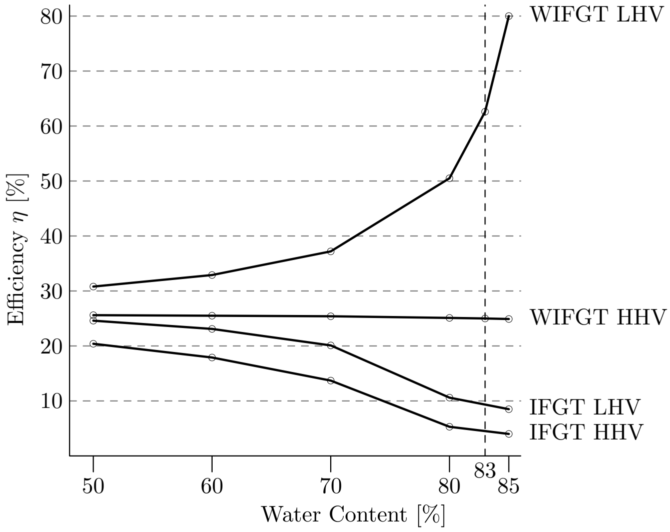

FIGURE 3. CALCULATED EFFICIENCY OF THE WET IFGT COMPARED TO A SIMPLE IFGT BASED ON BOTH LOWER AND HIGHER HEATING VALUE WITH TIT=591°C FOR ASSUMED VALUES OF COMPONENT PARAMETERS, SEE TABLE 2 (Elmegaard et al., 2001).

ratio unit with recuperation. A conversion to external firing can be achieved quite easily.

There are many types of industries in which the Wet IFGT may represent an attractive technology. Primarily, the process will potentially serve as a replacement in locations where biogas is the main source of heat and power production. The gas turbine operates with air at a high temperature and can thereby be integrated both for steam generation, high- and low- temperature heat production, and naturally will deliver power. Moreover, the IFGT is highly flexible with respect to choice of fuel due to the external combustion. In pure power-generation mode gas turbine technology has the advantage that no external cooling system is required.

CALCULATIONS OF THE PERFORMANCE OF A TYPICAL MICRO TURBINE AS WIFGT

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The first part of study was based on assumed values of the gas turbine operating characteristics. In this paper we present an analysis of the Wet IFGT based on characteristics of a typical, commercial micro gas turbine, for natural gas applications. In table 2 the component characteristics used in the modeling of the present study are shown. The assumptions made for the introductory part of the study were highly idealized and would be expected to result in unrealistically high efficiencies.

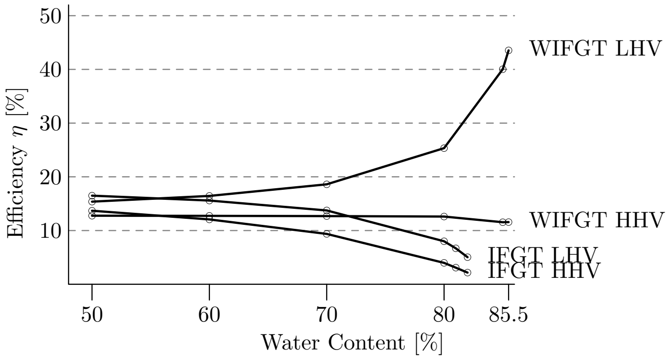

FIGURE 4. CALCULATED EFFICIENCY VERSUS FUEL MOISTURE CONTENT FOR AN IFGT BASED ON TYPICAL MICRO TURBINE DATA WITH TIT=591°C. SEE TABLE 2.

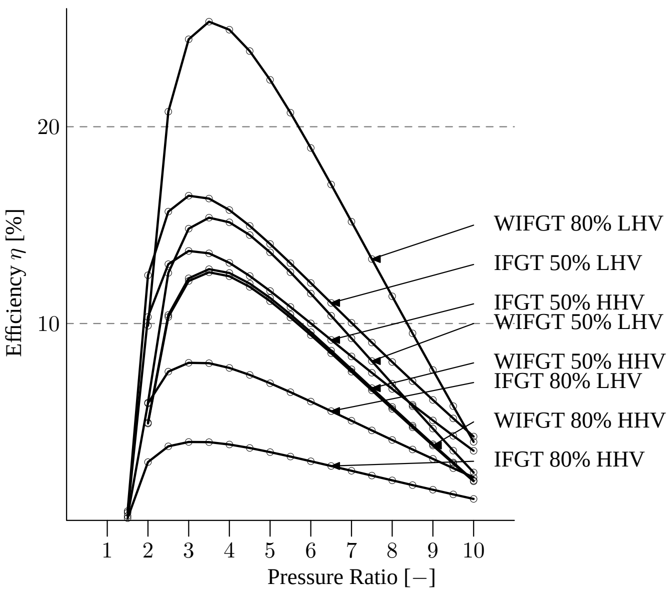

FIGURE 5. CALCULATED EFFICIENCY VERSUS PRESSURE RATIO OF A WET IFGT AND A SIMPLE IFGT BASED ON TYPICAL MICRO TURBINE DATA WITH TIT=591 °C.

Efficiency of a typical micro gas turbine as Wet IFGT

In figure 4 the efficiency of the Wet IFGT based on component characteristics supplied by Turbec is shown. It is found that the cycle based on the characteristics of the real turbine has significantly lower efficiency than was found for the introductory study. The main reason for the difference is that pressure losses were neglected in the introductory study, see table 2. It is also important to notice that the compressor and turbine of a typical micro turbine have lower efficiencies than formerly assumed. This leads to the conclusion that a Wet IFGT will not be better than an IFGT without fuel drying when operating on wood and biomass with less than 55% percent water, for this low value of maximum cycle temperature, $TIT = 591$°C. However, at fuel moisture contents higher than 55%, the drying will still exhibit a considerable improvement of the efficiency and the Wet IFGT will still be far better than competing biogas technology. (A simple IFGT will not be able to operate at high water content.)

It is observed that, compared to the introductory study, the real gas turbine will have the advantage that more heat is available for drying in the flue gas. A higher maximum fuel moisture content, 85.5% compared to 83% may be reached. This corresponds to a significant reduction amounting to 14.7% in solid content.

The calculated efficiency of the Wet IFGT as a function of pressure ratio is shown in figure 5.

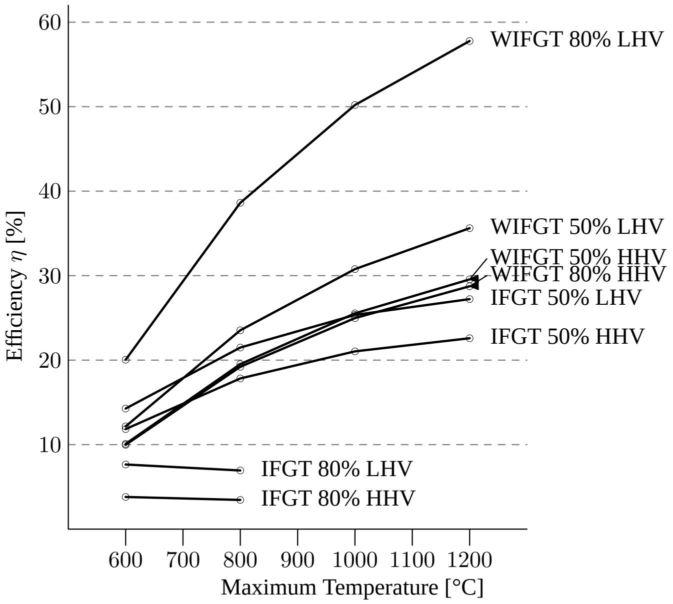

FIGURE 6. CALCULATED EFFICIENCY VERSUS MAXIMUM CYCLE TEMPERATURE FOR SIMPLE IFGT AND WET IFGT FOR TWO DIFFERENT FUELS WITH 50% AND 80% WATER CONTENT, RESPECTIVELY

Influence of Maximum Cycle Temperature

If material technology permits, the maximum cycle temperature, i.e., the gas inlet temperature to the heat exchanger, may be increased to more than the 700°C which is required for the TIT of 591°C, assumed for the calculations for figures 3 and 4. If so, the cycle will reach higher efficiency as shown in figure 6. The figure shows that there is a large benefit in achieving higher maximum temperatures for an Indirectly Fired Gas Turbine, both in the simple IFGT case and for the Wet IFGT. Current technology based on metallic materials will limit the maximum temperature to the heat exchanger to some 800°C and this will result in efficiencies of 23.5% and 38.6% for 50% and 80% moisture content, respectively, for a Wet IFGT. As shown in the figure a higher maximum temperature results in a higher efficiency and a more pronounced difference between the Wet IFGT and the simple IFGT.

Influence of Fuel Heating Value

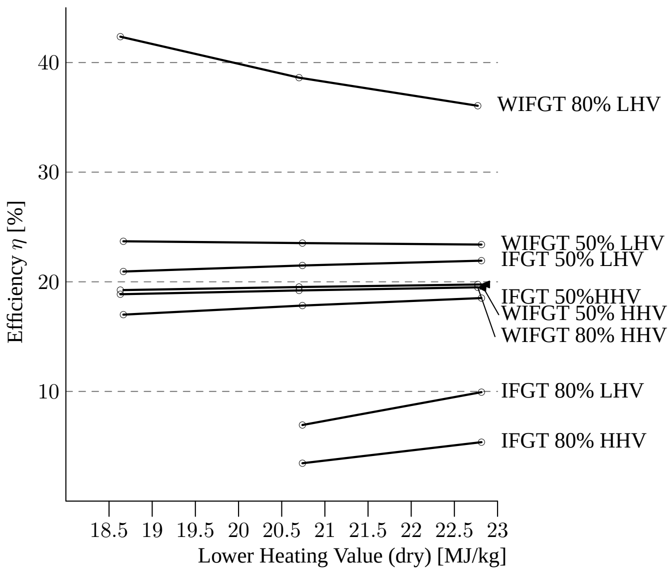

FIGURE 7. CALCULATED EFFICIENCY VERSUS LOWER HEATING VALUE FOR SIMPLE IFGT AND WET IFGT FOR A MAXIMUM TEMPERATURE OF 800°C AND TWO DIFFERENT FUELS WITH 50% AND 80% WATER CONTENT, RESPECTIVELY

Figure 7 displays the efficiency of the Wet IFGT and a simple IFGT process for a variation of $\pm$10% in lower heating value of the dry fuel. Mainly due to a better utilization of the thermal energy of the flue gas in the dryer, the efficiency of the Wet IFGT will be higher for lower heating values. This is in contrast to the simple IFGT in which the efficiency will be higher, the better the fuel is. For the Simple IFGT, fuel with low heating values will not contain enough energy to raise the temperature of the combustion products to the specified maximum temperature, 800°C.

In figure 8 it is seen that the heating value of the fuel influences the outlet temperature. It is seen that the use of higher quality-fuel will result in higher stack temperatures and thereby will permit a higher water content in the biomass. Table 3 shows

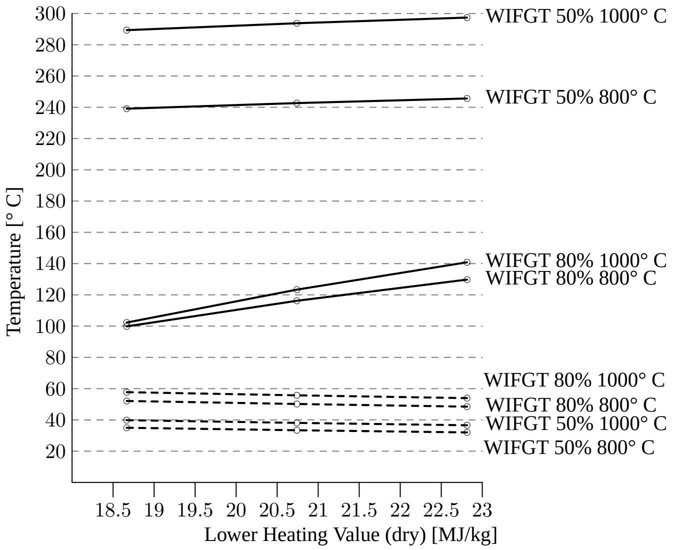

FIGURE 8. OUTLET TEMPERATURE AND DEW-POINT VERSUS LOWER HEATING VALUE FOR A WET IFGT FOR MAXIMUM TEMPERATURES OF 800°C AND 1000°C AND TWO DIFFERENT FUELS WITH 50% AND 80% WATER CONTENT, RESPECTIVELY

Dry Fuel Lower Heating Value [kJ/kg]	Maximum possible moisture content [%]	Efficiency [%]
18666	84.7	37.9
20740	86.0	38.0
22814	87.1	38.2

TABLE 3. CALCULATED EFFICIENCY AT THE MAXIMUM POSSIBLE FUEL MOISTURE CONTENT FOR A MAXIMUM CYCLE TEMPERATURE OF 600°C

this for a maximum temperature of 600°C. For each fuel the maximum efficiency is close to 38%, but the highest acceptable moisture content of the fuel is higher for the better fuels. For higher maximum temperatures the maximum moisture content is more or less the same, whereas the efficiencies that are achieved are increasing as shown in figure 6.

Corrosion

The most critical component in the cycle is the heat exchanger transferring heat from the combustion products to the air to the turbine expander. Corrosive attacks on the material of

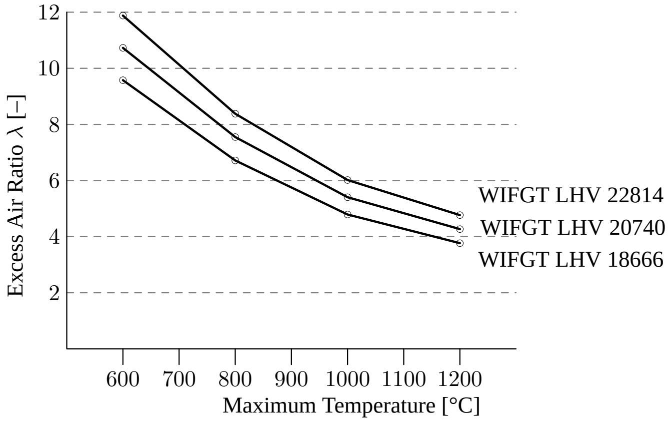

FIGURE 9. REQUIRED EXCESS AIR-RATIO FOR A WET IFGT

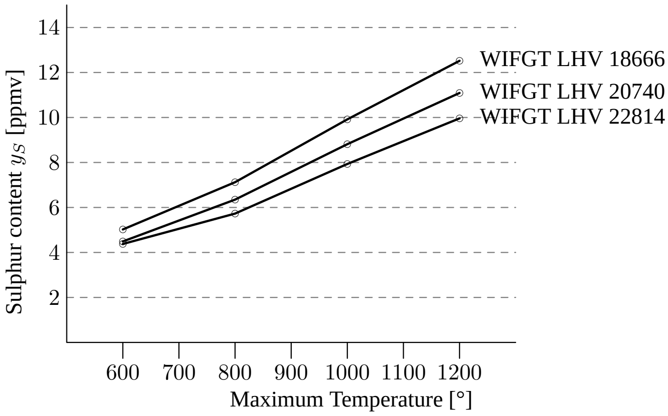

FIGURE 10. SULPHUR CONTENT IN COMBUSTION PRODUCTS FOR A WET IFGT

this component will depend on the choice of material, the temperatures and the corrosive components in the flue gas. Materials that are technically and economically sound and currently available will be metallic and can function up to temperatures around 800°C, but higher temperatures may be allowed depending on the amount of corrosives in the combustion products. This will depend on the type of fuel, the required maximum temperature, the turbine exhaust temperature and the water content after drying. The combustion chamber of the IFGT operates at a high excess air ratio. This is due to the fact that the combustion air is the high temperature exhaust of the turbine expander (see figure 9). This results in small contents of corrosives in the combustion products, thereby reducing the attack on the heat exchanger materials. In this case 0.04% Sulphur in the dry fuel, will result in a content of SO_2 in the combustion products below 13 ppmv. In waste sludges the content of Sulphur and other corrosives such as Chlorine, may be higher. This must be considered in the design of the heat exchanger.

Another approach to increasing the maximum temperature is to apply ceramics in the heat exchanger. This is an interesting option, but the development of coal-fired IFGT's with ceramic heat exchangers has not yet led to actual plant construction (Kumada, 1999; Robson and Seery, 1998; Tamme et al., 1998; Ferrato and Thonon, 1997; Shenker et al., 1997; Luzzatto et al., 1997; Solomon et al., 1996; LaHaye and Bary, 1994; Orozco, 1993; Orozco and Vandervort, 1993; Meunier, 1991; Henriette, 1991; Jahnig, 1986).

DISCUSSION

The computed results of the study demonstrate that the inclusion of pressure losses caused by flow friction and realistic values of component efficiencies are required to give realistic values of cycle performance.

The present study, in which values have been taken from current first generation micro turbine technology, and where the maximum heat exchanger temperature is governed by safety considerations, still shows that the Wet IFGT has a significant efficiency advantage compared to other small scale technologies applicable to very wet fuels.

Possible Technological Problems Several possible technological problems may have to be dealt with for a Wet IFGT operating on different waste sludges. Experience from parallel studies in Department of Mechanical Engineering, the Technical University of Denmark, from biogas plants, and other technical and agricultural studies may be of value in the coming developments of the Wet IFGT. Some of the problems which will have to be handled are the design and integration of the drying unit, and the design of the combustion chamber and the heat exchanger. In order to build a small-scale plant this integration has to be optimal. Furthermore, odor problems have been a key issue for biogas plants and industries trying to dry sludges. This problem, naturally, must be handled in order to make the Wet IFGT an interesting option in energy production.

Another problem to consider is toxic metals (heavy metals?) in the fuel.

CONCLUSION

The results of the study show that performance of the novel configuration, an IFGT, in combination with a drying unit, far exceeds the performance of the currently most popular commercially available competition, namely, power plants fueled by the gas from biogasification.

Because of the peculiarities of the conventional definitions of efficiencies in the biomass field, these far exceed the values that are commonly encountered in the gas turbine field. Furthermore, the choice of configuration results in a dilution of the corrosive gases and thus reduces the potential corrosive damage. The results of the study are so promising that we expect to continue with other financial support through design and construction of plants and through experimental work.

ACKNOWLEDGMENTS

We acknowledge Turbec's important contribution to this paper, by providing us with data for a typical, commercial micro gas turbine.

We also acknowledge the Danish Energy Agency and Nordic Energy Research Program for Process Integration for economic support of the work.

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Bilag C

Paper til præsentation ved ECOS 2002

THERMODYNAMIC ANALYSIS OF SUPPLEMENTARY-FIRED GAS TURBINE CYCLES

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ABSTRACT

This paper presents an analysis of the possibilities for improving the efficiency of an indirectly biomass-fired gas turbine (IBFGT) by supplementary direct gas-firing. The supplementary firing may be based on natural gas, biogas, or pyrolysis gas. The interest in this cycle arise from a recent demonstration of a two-stage gasification process through construction of several plants. A preliminary analysis of the ideal recuperated Brayton cycle shows that for this cycle any supplementary firing will have a marginal efficiency of unity per extra unit of fuel. The same result is obtained for the indirectly fired gas turbine (IFGT) and for the supplementary-fired IFGT. Both results show that the combination of external firing and internal firing have the potential of reducing or solving some problems with the use of biomass both in the recuperated and the indirectly fired gas turbine: The former requires a clean, expensive fuel. The latter is limited in efficiency due to limitations in material temperature of the heat exchanger. Thus, in the case of an IBFGT, it would be very appropriate to use a cheap biomass or waste fuel for low temperature combustion and external firing and use natural gas at a high marginal efficiency for high temperature heating. However, it is shown that this is not the case for a simple IBFGT supplementary fired with natural gas. Instead, other process changes may be considered in order to obtain a high marginal efficiency on natural gas. Two possibilities are analysed: Integration between an IFGT and pyrolysis of the biofuel which will result in a highly efficient utilization of the biomass, and integration between external biomass firing, internal biomass firing and internal natural gas firing. The marginal efficiency of the natural gas is in this case found to be independent of temperature ratio and lower than for the recuperated gas turbine.

NOMENCLATURE

c_p	Specific heat [kJ/kgK]
$\dot{m}$	Mass flow rate [kg/s]
PR	Pressure ratio [–]
$\dot{Q}_i$	Input heat flow rate [kJ/s]
$\dot{Q}_o$	Rejected heat flow rate [kJ/s]
T	Temperature [K]
T_h	Maximum temperature for internal combustion [K]
T_l	Ambient temperature [K]

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T_m Maximum temperature for external combustion [K]

TR Temperature ratio [–]

$\dot{W}$ Power [kW]

$\bar{\eta}$ Marginal efficiency [–]

η Efficiency [–]

κ Isentropic exponent [–]

$1 \ldots 7$ Indices defined in figures 2, 4 and 6

INTRODUCTION

The indirectly fired gas turbine (IFGT) has currently not reached a technological level making it commercially competitive. The main reason for this is that the cycle involves a heat exchanger transferring heat from the hot combustion products to the turbine inlet air. This requires the heat exchanger to operate at the highest temperature in the cycle. Material considerations and present designs limit the temperature of the heat exchanger to 700-800°C for metallic materials. The attainable efficiency will be limited by this maximum cycle temperature, and other ways to raise the process efficiency have to be explored. In this paper we propose supplementary direct firing as a way of raising the maximum cycle temperature, and thereby the efficiency of an IFGT, without exceeding the heat exchanger temperature limitation. This idea has been introduced in [22]. More recently, it has been studied by [17].

The paper addresses three different gas turbine cycles, i.e., a directly-fired, recuperated gas turbine; a simple cycle IFGT; and an IFGT with supplementary direct firing. For the latter we consider different fuels for supplementary firing in order to obtain either high efficiency on the biomass or high marginal efficiency on the more expensive fuel, the natural gas. The primary interest in this IFGT with supplementary firing is prompted by the development and demonstration through construction of two-stage biomass conversion plants. By careful control of temperatures this concept has the potential of retaining the environmentally objectionable and corrosive chemicals in the ashes while producing gas with tar contents of an acceptable magnitude.

This paper addresses only the ideal cycles, with reversible turbo machinery and ideal heat transfer. Gases are assumed to be perfect and having constant specific heat. The various gas turbines are described by air standard cycles.

History

The Indirectly Fired Gas Turbine (IFGT) has been under consideration for a long time [14, 22]. The driving force has almost exclusively been the possibility for using it for coal [7, 10, 19, 20], but also wood has been considered. However, a successful design has not materialized. This is due to the limited durability of the heat exchanger material in the presence of corrosive gases, the problem of fouling, and also because of the very high efficiencies achieved by the most important competitor, the modern coal-fired steam power plant.

IFGT's have been the subject of many theoretical studies, but the published efficiencies have been quite low. The main parameter of optimization has been the highest temperature of the cycle which is that of the combustion products at the inlet of the heat exchanger. Moreover, many studies have focused on the IFGT for application to coal-generated power [2, 7, 10, 11, 20]. One interesting reference on coal-fired IFGT's is the Ackeret-Keller-based plants, of which the oldest is the closed-cycle 2 MW plant which has been in operation since the 1950'es operating with a maximum temperature of 700°C [1]. This is a low temperature for gas turbines in general, also for operation on coal, but it will be shown below that operating temperatures in this range may still be interesting for micro gas turbines fueled with wet biomass.

The efficiency of Open-cycle simple IFGT's for biomass does not appear to be better than coal cycles. They are both limited by the same temperature. Also, in the smaller sizes, the high specific cost of high-temperature heat exchangers rules out the use of these. It should be noted that one gas turbine has been modified for “humid air” (HAT) application [18] and a number of novel concepts are subject to theoretical and experimental studies [3, 6, 21].

Activities in the Field at the Technical University of Denmark

The reported study is one of a number of projects aimed at the utilization of biomass for generation of electric power. These include fundamental research, modeling and demonstration of gasification of wood and straw, cofiring of biomass with coal, biomass-fired Stirling engines, and biogasification of biomass. The activities in the area of the IFGT started in 1994 and have resulted in two Master Theses [8, 15] and a few informal reports, but a very modest rate of progress. However, quite recently, theoretical studies of a power plant design based on the combination of a biomass drying unit with the IFGT have shown results with considerable promise [4, 5]. Results to date point to conversion efficiencies, that are higher by a factor of 3 to 10, relative to the best current competing technology, namely biogasification.

RECUPERATED GAS TURBINE

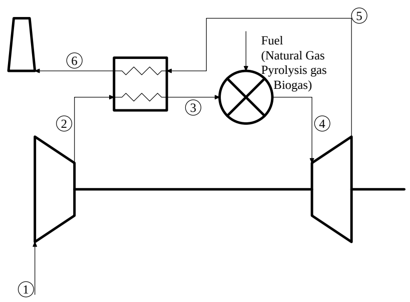

Figure 1: Flowsheet of a recuperated gas turbine

The flowsheet and the T-s-diagram of the recuperated gas turbine cycle are shown in figures 1 and 2, respectively. It consists of

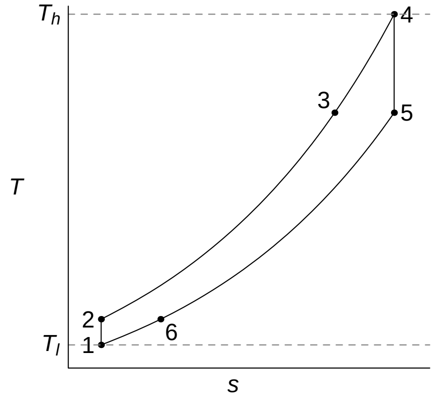

Figure 2: T-s-diagram for the Recuperated Gas Turbine Cycle

- isentropic compression from 1 to 2
- isobaric heating in recuperator from 2 to 3
- isobaric temperature increase in combustor from 3 to 4
- isentropic expansion from 4 to 5
- isobaric cooling in recuperator from 5 to 6

The net heat input to the cycle is:

$$\dot{Q}_i = \dot{Q}_{34} = \dot{m}c_p\,(T_4 - T_3) = \dot{m}c_p\,(T_4 - T_5) \tag{1}$$

The net heat rejected is:

$$\dot{Q}_o = \dot{Q}_{61} = \dot{m}c_p\,(T_1 - T_6) = \dot{m}c_p\,(T_1 - T_2) \tag{2}$$

By application of the relation between pressures and temperatures for isentropic state changes

$$TR_{is} = PR^{\frac{\kappa-1}{\kappa}} \tag{3}$$

it is found that:

$$\frac{T_2}{T_1} = PR^{\frac{\kappa-1}{\kappa}} \tag{4}$$

$$\frac{T_5}{T_4} = \frac{1}{PR^{\frac{1-\kappa}{\kappa}}} \tag{5}$$

and thereby after setting $T_1 = T_l$ and $T_4 = T_h$

$$\dot{Q}_i = \dot{m}c_p T_h\left(1 - \frac{1}{PR^{\frac{\kappa-1}{\kappa}}}\right) \tag{6}$$

$$\dot{Q}_o = -\dot{m}c_p T_l\left(1 - PR^{\frac{\kappa-1}{\kappa}}\right) \tag{7}$$

This leads to a power output of:

$$\begin{aligned}\dot{W} &= \dot{Q}_i + \dot{Q}_o \\ &= \dot{m}c_p \left(T_h \left(1 - PR^{\frac{1-\kappa}{\kappa}} \right) - T_l \left(1 - PR^{\frac{\kappa-1}{\kappa}} \right) \right)\end{aligned} \tag{8}$$

The efficiency of the process is defined as:

$$\eta \equiv \frac{\dot{W}}{\dot{Q}_i} = 1 - \frac{T_l}{T_h} \left(PR^{\frac{\kappa-1}{\kappa}} \right) \tag{9}$$

which equals the Carnot efficiency in the limiting case with $PR = 1$.

The marginal efficiency, i.e., the efficiency obtained by adding a small amount of fuel to reach a combustion temperature of $T_h + \Delta T_h$ is:

$$\overline{\eta} = \frac{\frac{\partial \dot{W}}{\partial T_h}}{\frac{\partial \dot{Q}_i}{\partial T_h}} \approx \frac{\Delta \dot{W}}{\Delta \dot{Q}_i} = \frac{\dot{m}c_p \Delta T_h (1 - PR^{\frac{1-\kappa}{\kappa}})}{\dot{m}c_p \Delta T_h (1 - PR^{\frac{1-\kappa}{\kappa}})} = 1 \tag{10}$$

This shows, that in the ideal case any supplementary firing will be thermodynamically favourable for the recuperated gas turbine.

INDIRECTLY FIRED GAS TURBINE

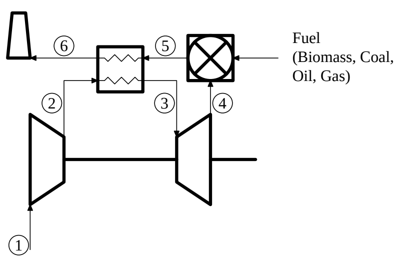

Figure 3: Flowsheet of an IFGT

The flowsheet and the T-s-diagram of the indirectly fired gas turbine cycle are shown in figures 3 and 4, respectively. It consists of:

- isentropic compression from 1 to 2
- isobaric heating in high-temperature heat exchanger from 2 to 3
- isentropic expansion from 3 to 4
- isobaric temperature increase in combustor from 4 to 5

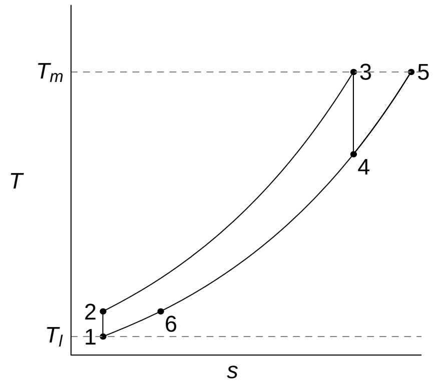

Figure 4: T-s-diagram for the Indirectly Fired Gas Turbine Cycle

- isobaric cooling in high-temperature heat exchanger from 5 to 6

The net heat input to the cycle is:

$$\dot{Q}_i = \dot{Q}_{45} = \dot{m}c_p (T_5 - T_4) = \dot{m}c_p (T_3 - T_4) \tag{11}$$

The net heat rejected is:

$$\dot{Q}_o = \dot{Q}_{61} = \dot{m}c_p (T_1 - T_6) = \dot{m}c_p (T_1 - T_2) \tag{12}$$

By application of equation (3) it is found that:

$$\frac{T_2}{T_1} = PR^{\frac{\kappa-1}{\kappa}} \tag{13}$$

$$\frac{T_4}{T_3} = \frac{1}{PR^{\frac{1-\kappa}{\kappa}}} \tag{14}$$

and thereby after setting $T_1 = T_l$ and $T_3 = T_5 = T_m$

$$\dot{Q}_i = \dot{m}c_p T_m \left(1 - \frac{1}{PR^{\frac{\kappa-1}{\kappa}}} \right) \tag{15}$$

$$\dot{Q}_o = -\dot{m}c_p T_l \left(1 - PR^{\frac{\kappa-1}{\kappa}} \right) \tag{16}$$

This leads to a power output of:

$$\begin{aligned}\dot{W} &= \dot{Q}_i + \dot{Q}_o \\ &= \dot{m}c_p \left(T_m \left(1 - PR^{\frac{1-\kappa}{\kappa}} \right) - T_l \left(1 - PR^{\frac{\kappa-1}{\kappa}} \right) \right)\end{aligned} \tag{17}$$

The efficiency of the process is:

$$\eta = \frac{\dot{W}}{\dot{Q}_i} = 1 - \frac{T_l}{T_m} \left(PR^{\frac{\kappa-1}{\kappa}} \right) \tag{18}$$

which is the same as for the recuperated cycle except for difference in maximum cycle temperature. Thus, the marginal efficiency found for raising the temperature to $T_m + \Delta T_m$ is also:

$$\bar{\eta} = \frac{\frac{\partial \dot{W}}{\partial T_m}}{\frac{\partial \dot{Q}_i}{\partial T_m}} \approx \frac{\Delta \dot{W}}{\Delta \dot{Q}_i} = \frac{\dot{m}c_p \Delta T_m (1 - PR^{\frac{1-\kappa}{\kappa}})}{\dot{m}c_p \Delta T_m (1 - PR^{\frac{1-\kappa}{\kappa}})} = 1 \quad (19)$$

Similar to the recuperated cycle, this indicates, that in the ideal case any supplementary firing would be thermodynamically favourable for the IBFGT.

INDIRECTLY FIRED GAS TURBINE WITH SUPPLEMENTARY FIRING

An indirectly fired gas turbine with supplementary direct gas firing is an interesting combination of the simple IFGT and the recuperated gas turbine. It has several technical advantages, because it will overcome the main problems with both of the two separate cycles.

Firstly, the recuperated gas turbine is directly fired and thus requires the fuel to be clean; usually natural gas in power applications. Natural gas is an expensive fuel, so an alternative of using a cheap fuel for the low-temperature part of the cycle, may be economically favourable.

Secondly, the introduction of heat into the IFGT is achieved in a high-temperature heat exchanger. Several studies [9, 12, 13, 16] have shown that the development of this component for very high temperatures for coal applications is very difficult. For biomass which may be more corrosive than coal, the maximum allowable temperature of the heat exchanger will be further constrained. With current technology this temperature should probably not exceed 700°C. This leads to a suggestion of a process with indirect biomass-firing and supplementary direct natural gas firing. A flowsheet and T-s-diagram of the cycle is shown figures 5 and 6, respectively. The process consists of:

- isentropic compression from 1 to 2
- isobaric heating in high-temperature heat exchanger from 2 to 3
- isobaric temperature increase in natural gas combustor from 3 to 4
- isentropic expansion from 4 to 5
- isobaric temperature increase in biomass combustor from 5 to 6
- isobaric cooling in high-temperature heat exchanger from 6 to 7

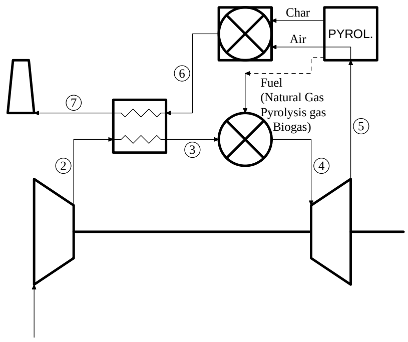

Figure 5: Flowsheet of an IFGT with supplementary firing

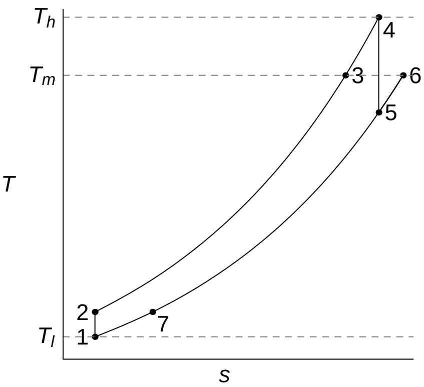

Figure 6: T-s-diagram for the Indirectly Fired Gas Turbine Cycle with supplementary firing

The net heat input to the cycle is:

$$\dot{Q}_i = \dot{Q}_{34} + \dot{Q}_{56} = \dot{m}c_p\,(T_4 - T_3) + \dot{m}c_p\,(T_6 - T_5) \quad (20)$$

The net heat rejected is:

$$\dot{Q}_o = \dot{Q}_{71} = \dot{m}c_p\,(T_1 - T_7) = \dot{m}c_p\,(T_1 - T_2) \quad (21)$$

By application of equation (3) it is found that:

$$\frac{T_2}{T_1} = PR^{\frac{\kappa-1}{\kappa}} \quad (22)$$

$$\frac{T_5}{T_4} = \frac{1}{PR^{\frac{1-\kappa}{\kappa}}} \quad (23)$$

and thereby after setting $T_1 = T_l$, $T_3 = T_6 = T_m$ and $T_4 = T_h$

$$\begin{aligned}\dot{Q}_i &= \dot{m}c_p\left((T_h - T_m) + \left(T_m - T_h\frac{1}{PR^{\frac{\kappa-1}{\kappa}}}\right)\right)\\ &= \dot{m}c_p\left(T_h\left(1 - \frac{1}{PR^{\frac{\kappa-1}{\kappa}}}\right)\right)\end{aligned} \tag{24}$$

$$\dot{Q}_o = -\dot{m}c_pT_l\left(1 - PR^{\frac{\kappa-1}{\kappa}}\right) \tag{25}$$

This leads to a power output of:

$$\begin{aligned}\dot{W} &= \dot{Q}_i + \dot{Q}_o\\ &= \dot{m}c_p\left(T_h\left(1 - PR^{\frac{1-\kappa}{\kappa}}\right) - T_l\left(1 - PR^{\frac{\kappa-1}{\kappa}}\right)\right)\end{aligned} \tag{26}$$

The efficiency of the process is:

$$\eta = \frac{\dot{W}}{\dot{Q}_i} = 1 - \frac{T_l}{T_h}\left(PR^{\frac{\kappa-1}{\kappa}}\right) \tag{27}$$

which is the same as for the recuperated cycle and the simple IFGT.
The efficiency of the IFBGT cycle, i.e., the biomass part of the supplementary fired cycle, with a combustion temperature of T_m is as in (18)

$$\eta = \frac{\dot{W}}{\dot{Q}_i} = 1 - \frac{T_l}{T_m}PR^{\frac{\kappa-1}{\kappa}} \tag{28}$$

{which means that the value of the marginal efficiency for this cycle also is unitywhich also means that the marginal efficiency obtained by supplementary firing and thereby raising the maximum temperature to T_h equals 1. The fuel added to get from T_m to T_h is given by:

$$\Delta\dot{Q}_i = \Delta\dot{W} = \dot{m}c_p(T_h - T_m)\left(1 - PR^{\frac{1-\kappa}{\kappa}}\right) \tag{29}$$

but, the amount of natural gas added is larger than the change in fuel consumption. It is:

$$\dot{Q}_{ng} = \dot{m}c_p(T_h - T_m) \tag{30}$$

This gives a marginal efficiency for the natural gas of:

$$\bar{\eta} = \frac{\Delta\dot{W}}{\dot{Q}_{ng}} = 1 - PR^{\frac{1-\kappa}{\kappa}} \tag{31}$$

It is observed that this is only dependent on the pressure, and thus independent of the temperatures in the cycle. Furthermore, the value is lower than the efficiency achieved by a simple recuperated gas turbine cycle working between T_l and T_h (see equation 9). The simple supplementary firing scheme therefore is not an advantage when trying to increase the marginal efficiency of natural gas. However, it does raise the efficiency of an IBFGT and may be acceptable for this reason.
It should be noted that if the biofuel is costless, e.g., a waste stream from an industrial plant, the total power production may be considered as an output from the natural gas consumption making the marginal efficiency on natural gas exceed unity. This is a further complication of matters, however, and is not discussed further.
Two alternatives present themselves:

- If the biofuel can be divided into two streams, one for indirect and one for direct firing, a high marginal efficiency on supplementary internal firing is reached. The separation of the fuel in two parts, a “clean” gaseous fuel for internal firing and a “dirty” residue for external firing may be accomplished by pyrolysis, or by thermal or biological gasification.

- Furthermore, if an amount of “clean” gaseous biofuel, equal to or greater than:

  $$\Delta\dot{Q}_b = \dot{m}c_p(T_h - T_m)PR^{\frac{1-\kappa}{\kappa}} \tag{32}$$

  is available without cost (see equations 28 and 29), it may be fired internally concurrently with the natural gas, and then the marginal efficiency of electric power produced by the natural gas may even exceed unity. In order to realize such a cycle, a number of constraints on the temperatures in the process stages will have to be introduced. This option is however, highly dependent definitions of efficiency and assignment of cost to the different fuels.

DISCUSSION

In this paper we have considered the overall thermal efficiency (total fuel input to total power output) and the marginal efficiency (added fuel input to increased power output) only. However, in a cycle with more than one fuel input several alternative measures of efficiency may be applied, depending on which fuel is considered to be the basic input and how much of the produced power that is considered to be produced by each fuel. Thus, depending on cost of the different fuels and power alternative measures of quality may be preferred. In any case, the most important factor for the evaluation of an IFGT with or without supplementary firing will be an assessment of the overall economics of the installation. In future studies we will incorporate both economic aspects and component data for real gas turbines.

CONCLUSION

We have shown that, in the ideal case, a recuperated, an indirectly fired and an indirectly/supplementary-fired gas turbine will have the same efficiency. This is naturally not the case for a real application, but the analysis has provided a deeper insight into the paths to follow in order to find IFGT cycles with sufficiently high efficiency compared to alternative options for biomass applications.

The IFGT with supplementary firing may both be applied for achieving a higher total efficiency than possible with external firing only, and for achieving a high marginal efficiency with an expensive fuel. In both cases there are restrictions however. In the former case the supplementary firing and the basic firing have to be provided by the same biomass requiring pretreatment of the fuel for instance by pyrolysis, thermal gasification, or biogasification. In the latter case, part of the cheaper fuel has to be burned internally, concurrently with the expensive fuel. Thus, a pretreatment of the cheap fuel is also demanded in this case.

The conclusion must, however, be that in view of the recent demonstration of two-stage gasification, the IFGT should be given more attention in the future research on biomass applications. The present conclusive observation is that the main hindrance for its commercialization, the need to develop high-temperature heat exchangers, may to some extent be compensated for by process modifications.

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