Abstract

In this thesis energy, exergy and exergoeconomic analysis has been carried out on a different number of co-generation energy systems involving cooling. The models and methods developed can be used as a frame work to improve the district heating and cooling system thermodynamically and/or economically which is the objective of the PhD project.

A thermodynamic (energy and exergy) model of a transcritical CO_2 cooling and heating system has been developed. The coefficient of performance (COP) of the system is the characteristic of interest. A sensitivity analysis of the parameters: compressor isentropic efficiency, effectiveness of the internal heat exchanger, pressure losses and the pinch temperatures in the heat exchanger on the COP has been carried out. The results show that the COP is most sensitive to the following order of parameters: compressor isentropic efficiency, pinch temperature in the gas cooler, pinch temperature in the evaporator and effectiveness of the IHX. These results are complemented by the exergy analysis, where the exergy destruction ratio of the CO2 system's component is found.

Heat recovery from vapour compression heat pumps has been investigated. The heat is to be used in a district heating system based on combined heat and power plants (CHP). A theoretical comparison of trigeneration (cooling, heating and electricity) systems, a traditional system and a recovery system is carried out. The comparison is based on the systems overall exergy efficiency. The traditional system consists of a combined heat and power (CHP) plant with a separate refrigeration plant, where its condenser heat is rejected to the environment. The recovery system consists of the same CHP plant but with a heat pump, where the condensation heat is recovered.

Five different refrigerants (R717, R600a, R290, R22 and R143a) are chosen to be representative for current refrigeration plants of the traditional and recovery system. Also different refrigeration cycle, one and two stage cycle is considered. The CHP plants considered is back-pressure and extraction plant.

In general heat recovery is more beneficial if the district heating system is based on back-pressure rather than on extraction CHP plant. Heat recovery with extraction CHP plant is in general questionable. If heat recovery is considered it is recommendable to use two stage cycle rather than one stage cycle heat pump.

Apportioning the costs of different energy services which are produced by the same energy system is not trivial. As an example the cost of heating and cooling provided simultaneously by an ammonia heat pump has been apportioned with two costing methods – energy and exergy costing. Parametric study on the heating, cooling and surrounding temperature has been carried out. It has been demonstrated that the two methods yield significantly different results. Energy costing prices the unit cost of heating and cooling equally independent of the quality of the heat transfer, and it tends to overprice the cost of cooling in an irrational manner. Energy costing will also not encourage rational heating and cooling temperature demand and thus will not promote efficient use of resources. These flaws are not seen with exergy costing, since it has taken the

quality of heat transfer in to account. Consequently the exergy costing method is found to be the more rational apportioning method for simultaneous district heating and cooling.

The methodology of the exergy costing method can also be used to calculate the environmental impact of each consumer. Taxation can eventually be based on this. The method is called exergoenvironmental analysis. As a principle example, the CO2 emission for each of the cooling and heating consumer is found. The conclusion is analogue to the exergy costing method, i.e. the exergoenvironmmental method can be used as motivation for reducing CO2 emission.

One of the main obstacles with district cooling in a traditional water based system is the investment cost for the pipes. To overcome this, a combined district heating and cooling system based on CO2 as refrigerant and transport fluid is proposed.

Exergoeconomic analysis has been used to evaluate and optimize a CO2 based system for combined heating and cooling. The exergoeconomic method SPECO is used. The system has variable demands which lead to structure change, a difficult challenge for exergoeconomic methods. Structure change in an energy system is when not all of its components are operating in the same time and/or the direction of the fluids change direction. For handling these issues time weighted average of the exergoeconomic variables has been calculated. Based on these variables iterative optimization is carried out. For comparison the CO2 system is also optimized by a direct search method, which results are considered as the true optimized value within four significant digits. The exergoeconomic method tends to converge to the results of the direct search. The computing time is lower for the exergoeconomic method compared to the direct search method. The difference will be more pronounce in favor of the exergoeconomic method, when the system's complexity increases. It can therefore be conclude that the exergoeconomic method using time weighted average exergoeconomic variables is applicable for the CO2 system with varying demands and structure change.

Resumé

(Danish abstract)

I denne afhandling er der udført energi, exergi og exergoeconomic analyser af en række forskellige energi systemer, som involverer køling. Heraf er der blevet udviklet metoder og modeller, som kan bruges som skabelon til at forbedre fjernvarme og køling systemer termodynamisk og/eller økonomisk, hvilket er formålet med Ph.d. projektet.

En termodynamisk (energi og exergi) model af et transkritisk CO2 køle og varme system er blevet udviklet. Systemets effektivitet er udtrykt ved begrebet COP, hvor dets afhængighed af forskellige parameter er blevet undersøgt i form af en sensitivitets analyse. Resultatet viser, at denne analyse bekræfter og komplementere exergi analysen. Exergi analysen har udregnet den relative exergi ødelæggelsen i de forskellige komponenter af CO2 systemet.

Varmegenindvinding fra kompressions køle anlæg har været undersøgt. Der er foretaget en teoretisk sammenligning af to forskellige trigeneration systemer (køl, varme og el) – et traditionel system uden varme genindvinding og et med varmegenindvinding. Sammenligningen er baseret på exergi effektiviteten. Det traditionelle system består af en kombineret kraftvarme værk med separate kølingsanlæg, hvor kondenseringsvarmen bortledes til omgivelsen. Det andet system med varme genindvinding består af samme varme-kraft værk men med en varmepumpe, som kan lede kondenseringsvarmen til et fjernvarme net.

Forskellige typer varmepumper er blevet anvendt i sammenligningen. Disse er med køle middel R717, R600a, R290, R22 og R143a, og som et- eller to-trins kreds. To type kraftværker er anvendt: modtryks- og udtagsværk.

Generelt viser resultaterne at varme genindvinding er mest fordelagtigt, hvis systemet er baseret på et modtryksværk frem for et udtagsværk. Hvis varme genindvinding overvejes, bør det været baseret på 2-trins kreds.

Fordeling af omkostningerne på forskellig energi produkter, som er produceret af samme anlæg kan være kompliceret. Et eksempel er vist med en ammoniak varmepumpe, som kan levere køling og opvarmning samtidig. Der er anvendt to måder at fordele omkostningerne på: en energi baseret økonomisk analyse og en exergi baseret analyse. Metoderne giver vidt forskellige resultater. Med energi metoden er omkostningen per enhed køl og varme den samme. Dette kan medføre uhensigtsmæssigt brug af energi. Med exergi metoden derimod, er omkostningerne forskellige for køl og varme, og er meget afhængig opvarmnings- og kølingstemperaturene. Hvis priserne fastsættes på bagrund af exergi metoden, kan forbrugerne motiveres til at bruge opvarmning og køling med de mest hensigtsmæssige temperature. Det vil i den sidste ende reducere energi behovet for hele systemet.

Exergi metoden kan også bruges til at fordele ansvaret for miljøbelastningen. For eksempel kan man udregne, hvor meget den enkelte forbruger har ansvaret for udledning af CO2. Dette kan dannes grundlag for en beskatnings metode, der motivere forbrugerne i at udlede mindst muligt CO2.

En af de største ulemper ved fjernkøling er investeringsomkostninger for rørsystemet. Dette kan løses med et kombineret fjernvarme og kølings anlæg baseret på CO2. Dette system består af kun to rør, mens det traditionelle består af fire, to for fjernvarme og to for fjernkøling.

Exergoeconomic analyse i form af SPECO metoden er blevet brugt til at analysere og optimere et kombineret fjernvarme og kølings anlæg baseret på CO2. Anlægget har varierende forbrug hen over året, som fører til struktur ændringer af anlægget. For at håndtere denne problem stilling er der udregnet en række tidsvægtet exergoeconomic variabler. Ud fra disse kan anlægget termoøkonomisk optimeres ved en iterativ proces, som er udviklet til SPECO metoden. Resultatet er sammenlignet med en anden matematisk metode, kaldes *direct search*. Denne metode giver den globale optimal løsning, men er mere tidskrævende, og vil ikke være egnet til større systemer med mere fluktuerende forbrug. Exergoeconomic resultatet har tendens til at konvergere mod *direct search* resultatet. Dermed viser SPECO metoden sig at være brugbare for disse typer systemer. Den termoøkonomiske model og optimeringen udviklet her kan bruges som skabelon for et virkeligt anlæg.

Metoderne og analyserne præsenteret i afhandlingen kan bruges som skabelon til at forbedre fjernvarme og kølings systemer termodynamisk og/eller økonomisk.