

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**EVALUATION OF ENERGY EFFICIENCY OF A
POWER-PLANT USING ENERGY ANALYSIS**

by
Ahmet Yakup CUMBUL

July, 2018
İZMİR

EVALUATION OF ENERGY EFFICIENCY OF A POWER-PLANT USING ENERGY ANALYSIS

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Master of Science of
Department of Mechanical Engineering**

**by
Ahmet Yakup CUMBUL**

**July, 2018
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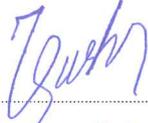
M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “EVALUATION OF ENERGY EFFICIENCY OF A POWER-PLANT USING ENERGY ANALYSIS” completed by AHMET YAKUP CUMBUL under supervision of PROF. DR. DİLEK KUMLUTAŞ and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.



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EVALUATION OF ENERGY EFFICIENCY OF A POWER-PLANT USING ENERGY ANALYSIS

ABSTRACT

Today, when the influence of electricity and heat production on the environment is examined, the efficiency of power plants is very important. For this reason, besides electricity generation, waste heat recovery should be used in almost every system. Although they are higher in terms of initial investment costs, waste heat recovery systems soon meet their own investment costs. After the cogeneration systems, trigeneration systems are used for both heat and refrigeration needs. Combined Cooling Heating and Power (CCHP) is an extended form of the cogeneration system. In addition to cogeneration, heat recovery is used in cooling as well as heating.

In the present study, a trigeneration system of a city hospital with a capacity of 3660 beds in Ankara, Turkey is modeled as thermodynamically. There are 4 groups of 4300 kW_e generators in the trigeneration system. For each generator set, there are one hot water boiler and absorbed chiller exist for the waste heat recovery. In this system, three different waste heat recovery is done on the engine side of the generator. These are JW (jacket water), AC (after cooler) and LUBOIL (oil cooling) circuits. Trigeneration system meets entire electricity demand of the hospital. The heating circuits provides 18.7 percent of the heat requirement and the cooling circuit on the other hand, provides 17.2 percent of the cooling demand.

Combustion inside the engine (combustion chamber) is modelled by an in-house code that is developed in this thesis. Combustion is modelled to automatically estimate the ideal gas phase thermodynamic properties. This code is written in GO (GOLang) for use on machines running under MSDOS.

Keywords: Combustion, trigeneration, thermodynamic analysis

ENERJİ ANALİZ METODUYLA BİR ENDÜSTRİ TESİSİNİN ENERJİ VERİMLİLİĞİNİN DEĞERLENDİRİLMESİ

ÖZ

Günümüzde, elektrik ve ısı üretiminin çevre üzerindeki etkisi incelendiğinde, enerji santrallerinin verimliliği çok önemlidir. Bu nedenle, elektrik üretiminin yanı sıra, hemen her sistemde atık ısı geri kazanımı kullanılmalıdır. İlk yatırım maliyetleri açısından daha yüksek olmalarına rağmen, atık ısı geri kazanım sistemleri kısa sürede kendi yatırım maliyetlerini karşılamaktadır. Kojenerasyon sistemlerinden sonra, hem ısı hem de soğutma ihtiyaçları için trijenerasyon sistemleri kullanılmaktadır. Bütünleştirilmiş ısıtma, soğutma ve güç sistemi (CCHP), kojenerasyon sistemlerinin genişletilmiş bir şeklidir. Kojenerasyona ek olarak, ısı geri kazanımı, soğutmada ve aynı zamanda ısıtmada kullanılır.

Bu çalışmada Ankara bölgesinde 3660 yatak kapasiteli bir şehir hastanesinin trijenerasyon sistemi termodinamik olarak modellenmiştir. Trijenerasyon sisteminde 4 grup 4300 kWe gücünde jeneratör vardır. Her jeneratör seti için, bir adet sıcak su kazanı ve atık ısı geri kazanımı için absorpsiyonlu çiler bulunmaktadır. Bu sistemde, jeneratörün motor tarafında üç farklı atık ısı geri kazanımı yapılır. Bunlar JW (ceket suyu), AC (after cooler) ve LUBOIL (yağ soğutma) devreleridir. Trijenerasyon sistemi, hastanenin tüm elektrik ihtiyacını karşılamaktadır. Isıtma çevrimi durumunda, ısı ihtiyacının yüzde 18,7'sini sağlar öte yandan soğutma çevrimi durumunda ise soğutma ihtiyacının yüzde 17,2'sini sağlar.

Motor içindeki yanma (yanma odası), yazılımla modellenmiştir. Yanma, ideal gaz durumunda termodinamik özellikleri hesaplamak için modellenmiştir. Bu kod, GO (GOLang) dilinden yazılmış olup, MSDOS altında çalışmaktadır.

Anahtar kelimeler: Yanma, trijenerasyon, termodinamik analiz

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Following the oil crisis of the early seventies, energy efficiency has become one of the top priorities in the world. Power plants that use fossil fuels (natural gas, gasoline, LNG and so on.) in electricity generation, have turned to heat recovery to increase their energy efficiency. Besides electricity production, cogeneration systems are used in facilities which has heat requirements. It is also used in combined cycle power plants to increase electricity production through steam turbines for steam production.

Albisu (2003) described cogeneration as the simultaneous production of electricity and thermal starting from a single fuel. In most cases, a cogeneration facility produces the total plant heat requirements plus electricity which, complemented if necessary by purchasing from the grid, is also consumed in the plant; alternatively, electricity produced in excess of plant requirements is sold to the grid. Either of these situations can be permanent or interchangeable daily and seasonally. A cogeneration installation at an industrial plant will reduce transmission losses and make thermal energy usable that would otherwise be lost. Overall efficiency of cogeneration can reach up to 90%.

Trigeneration is one of the cogeneration models which can also produce cooling instead of heating. Trigeneration system is a preferred model where there is a need for cooling as well as a need for heating. This is applied for facilities especially which need uninterrupted energy like hospitals, shopping malls, and airports.

1.2 Objective

The aim of this study is to calculate overall system efficiency of a trigeneration system. For this purpose, a code was developed for combustion process to identify the engine efficiency. This software can be thought as a package for calculating the combustion enthalpy, exhaust composition, exhaust temperature and flow rate. Useful

parts of this package are can be work with any other program for input values. For example, calculating exhaust composition for duct firing HRSG (Heat Recovery Steam Generator) modules or burner combustion units. Also, can be used for evaluating the electrical and thermal efficiencies of the power plants.

In this study, system efficiency of a trigeneration system in a hospital calculated. The thesis primarily focused on investigating the effects of combustion on performance and efficiency by examining the concepts of combustion. Also, with a heat recovery, investigating system efficiency variations for heating or cooling progresses.



CHAPTER TWO

LITERATURE REVIEW

2.1 Combined Power Plants

Ganjehkaviri, Jaafar & Hosseini (2014) revealed, among different kinds of power plants, combined cycle power plants (CCPPs) gained a lot of attentions due to the fact that they are attractive in power generation field because of higher thermal efficiency rather than individual gas turbine or steam power plants. In addition, they are also important due to their relatively high energy efficiencies, low pollutant and greenhouse gas emissions, and operational flexibility.

Polyzakis, Koroneos & Xydis (2007) mentioned that, for years, the gas turbine has mainly been operated in a simple cycle. It consists of one stage of compression, a single heat input stage and simple expansion through a turbine. Possible additions to this cycle are intercooling, reheat or a combination of these. The dashed heat rejection lines are given in Figure 2.1 indicate that it is an open cycle, meaning that new working fluid like air and fuel are continuously put through the cycle. Although this is, by far, the most common practice, closed gas turbine cycles where the heat is supplied through a heat exchanger (so called indirectly fired cycles) are gaining renewed interest. when considering a combined cycle including a gas turbine, the Rankine steam cycle is simply added underneath the Brayton cycle. The Brayton topping cycle rejects its heat to the Rankine bottoming cycle to raise steam, instead of directing it to the atmosphere as in the single cycle configuration. For obvious reasons, this principle is called “waste heat recovery” and the steam raising device substituting for the boiler of a conventional steam plant is called the heat recovery steam generator (HRSG). The combined cycle plant thermal efficiency is defined by;

$$\eta_{CC} = \frac{(work\ output)_{CC}}{(heat\ input)_{GT}} \quad (2.1)$$

$$\eta_{CC} = \frac{net\ GT\ work + net\ ST\ work}{fuel\ energy\ input\ into\ GT} \quad (2.2)$$

Clearly, the efficiency of the combined gas/steam cycle is higher than that of the gas turbine by itself. However, where the optimization of one cycle was relatively simple, i.e., a matter of raising the mean temperature of heat reception and lowering that of heat rejection, the optimization of the CC (Combined Cycle) is a more complicated matter. T-S diagram and the basics of the combined heat and power plant is shown in Figure 2.1.

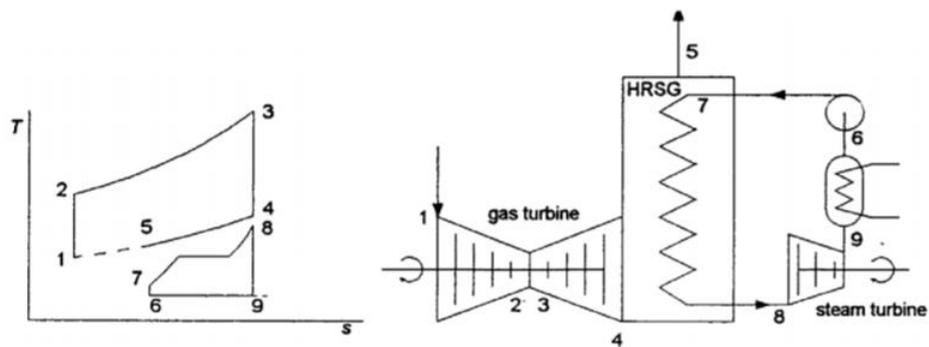


Figure 2.1 T – S diagram and the basics of the Combined Heat and Power Plant, (Polyzakis, Koroneos & Xydis, 2007)

2.2 Trigeneration Power Plants

The most important goal of a trigeneration system is getting chilled energy as well as heating energy. In trigeneration system we may use absorption or multi chiller for the cooling. Basics of a trigeneration system are given on Figure 2.2.

Santoyoa & Cifuentes (2003) mentioned that, Trigeneration, also referred to as district energy, achieves a higher efficiency and smaller environmental impact than cogeneration. The installation of a trigeneration plant can achieve up to a 50% greater system efficiency than cogeneration plant of similar size. A trigeneration plant is often described as a cogeneration plant that has added absorption chillers (MRA), which take the waste heat a cogeneration plant would have wasted and converts this free energy into useful energy in the form of chilled energy.

Seyedan, Dhar & Gau (American Society of Mechanical Engineers (ASME), 1996) mentioned that, since the WHRB (waste heat recovery boiler) is the equipment that couples the two power-producing cycles of a combined cycle power plant, any change in its design influences the power output of both the steam cycle and gas turbine cycle. While carrying out the search for optimal design of a WHRB, it is therefore essential to estimate the power output of a CCHP for every potential design and choose only those designs that give the total output equal to (or greater than) the rated output of power station. A procedure for simulation of combined cycle power plant is therefore a prerequisite for developing a procedure for optimum design of a WHRB.

2.3.1 Components of the Waste Heat Recovery System

In a common trigeneration system, there are two types of heat recovery systems exists. One of this recovery is from exhaust gas flow. For a gas engine, exhaust temperature can be reach up to 500 °C. WHRB generates hot water, steam, hot oil and so on from exhaust gas. On the other hand, engine cooling systems has heat exchangers for the waste heat recovery. Hot water to be produced from engine cooling systems can be used for heating and also cooling. For heating process, heat exchangers are used. For cooling process hot water is used with absorption chiller.

CHAPTER THREE

MATHEMATICAL MODELLING

3.1 Mathematical Modelling Method

In mathematical modelling, calculation of the thermophysical properties is done by Brant (1995). Calculations and the coefficients is used by NASA (1963). Calculations of the enthalpy and the temperature is written in code by these sources and modelled into software.

3.2 Mathematical Modelling of Combustion

In many technical applications, it can be assumed that the gases are sufficient ideal gas for the dynamic approaches. The specific heat capacity and the enthalpy can be considered as becoming pressure independent.

Ideal gases exist between the molar mass (M), the density (ρ_n) in the standard state, the gas constant R , the molar gas constant R_m and the normal volume (V_{mn}) can be thought as existing together:

$$p_n = \rho_n R T_n \quad (3.1)$$

$$p_n V_{mn} = R_m T_n \quad (3.2)$$

$$R = \frac{R_m}{M} \quad (3.3)$$

$$v_n = \frac{1}{\rho_n} = \frac{V_{mn}}{M} \quad (3.4)$$

With,

- $p_n = 101325 \text{ Pa}$
- $T_n = 273.15 \text{ K}$

$$R \rho_n = \frac{p_n}{T_n} = 0.37095 \left[\frac{\text{kJ}}{\text{m}^3 \text{K}} \right] \quad (3.5)$$

$$\bar{v}_{mn} = R_m \frac{T_n}{P_n} = \frac{R_m}{0.37095} \left[\frac{m^3}{kmol} \right] \quad (3.6)$$

In the limiting case $P \rightarrow 0$, the molar gas constant is the same for all gases. This value is called as the universal gas constant;

$$R = 8.31441 \left[\frac{kJ}{kmol K} \right] \text{ thus, } \bar{v} = 22.41383 \left[\frac{m^3}{kmol} \right]$$

For the representation of the specific volume v (density $\rho = 1/v$), the ideal gas law can be applied as:

$$v = v(p, T) = R \frac{T}{p} \quad (3.7)$$

With the caloric state value, it suffices to represent the temperature dependence of a variable by an empirical equation. When the caloric state value suffices, during an empirical equation a variable of temperature dependence can be represented. The other quantities can be accepted over the thermodynamic relationships. The temperature dependence of the spec. heat capacity at constant pressure can be given as:

$$c_p = f(T) = \frac{dh}{dT} \quad (3.8)$$

The enthalpy is then;

$$dh = c_p dT \quad (3.9)$$

$$h = \int_{T_n}^T f(T) dT \quad (3.10)$$

$$u = h - pv = h - RT \quad (3.11)$$

$$c_v = \frac{du}{dT} = \frac{dh}{dT} - R = c_p - R \quad (3.12)$$

The integral for the calculation of the enthalpy has the limits T_n and T ; that is to say, as the zero point is chosen for the enthalpy of the standard state ($T = 273.15 K$, $p = 1.01325 \text{ bar}$). For the caloric state value is h^* and g^* , the standard physicochemical

state is chosen ($T_0 = 25\text{ }^\circ\text{C}$, $T_0 = 298.15\text{ K}$, $P = 1\text{ atm} = 1.01325\text{ bar}$) as the dead state properties.

To calculate chemical equilibria one needs the caloric quantities including the enthalpy of formation;

$$h^* = h + h_0^* = \int_{T_0}^T f(T)dT + h_0^* \quad (3.13)$$

The enthalpy of formation in the standard state is h^* .

3.2.1 NASA Polynomials

NASA (1963) gives equations for 210 substances and the widely used 18 elements. If one relates the ambient state variables to the gas constant or to the gas constant and the temperature, dimensionless expressions result as;

$$\frac{c_p}{R} = F(T) \quad (3.14)$$

$$\frac{h}{RT} = \frac{1}{T} \int_{T_n}^T f(T)dT \quad (3.15)$$

$$\frac{h^*}{RT} = \frac{1}{T} \int_{T_0}^T f(T)dT + \frac{h_0^*}{RT} \quad (3.16)$$

In the NASA (1963), for the representation of the temperature dependence polynomials of fourth degree is used. Since with such a polynomial the desired temperature range of 300 to 5000 K cannot be represented with sufficient accuracy, two polynomials of the fourth degree are used. The first polynomial reflects the temperature range of 300 to 1000 K, the second the range of 1000 to 5000 K.

h^* can be calculated with a polynomial of fourth degree as;

$$\frac{h^*}{RT} = a_1 + \frac{a_2}{2}T + \frac{a_3}{3}T^2 + \frac{a_4}{4}T^3 + \frac{a_5}{5}T^4 + \frac{a_8}{T} \quad (3.17)$$

Coefficients of equation has given in Table 3.1.

The ambient state quantities can be calculated with a fourth degree polynomial with eight coefficients, whereby the thermodynamic consistency is ensured. For the second polynomial one, then, needs another set of eight coefficients (a_9 to a_{16}). It should be noted that the coefficients a_8 , a_9 , a_{14} , a_{15} and a_{16} are not independent of the coefficients a_1 to a_7 and a_{10} to a_{13} . They result from the conditions that at the validity limit $T_B = 1000$ K both polynomials for c_p , h and h^* give the same value, and that for $T_n = 273.15$ K the enthalpy must become zero.

Since, for the calculation of the polynomial coefficients, the measured molar temperatures were made dimensionless with the universal gas constant R_{m0} , R_{m0} must also be used in the back calculation into dimension-related quantities, that is to say, one receives the mass unit related spec. value by using the individual gas constant $R = R_{m0} / M$, and the kilomole-related spec. value by using $R = 8.31441$ kJ/kmol·K.

In the NASA (1963) the measured molar temperatures are with the universal Gas constants $R_{mo} = 1.98718$ cal/mol·K dimensionless, that is, it was the value related to the thermochemical calorie. In order not to have to pay attention to practical calculations, the polynomial coefficients of the NASA report converted as if in today's thermodynamics standard. International calorie related gas constant $R = 1,985,886$ cal_{int} / mol·K would have been used (1 cal_{int} = 4.1868 kJ). Therefore, the coefficient of these values have been multiplied by the factor 1.000665.

The values tabulated in Table 3.1 are therefore no longer in numerical terms of NASA (1963) specified values. On the other hand, the enthalpy is recorded as accepted. The integration constant a_8 is calculated so that the enthalpy at 0 °C ($T_n = 273.15$ K) becomes zero. The NASA report only states h^* . Another note required about the upper temperature limit of 5000 K is necessary. In Table 3.1 the polynomial coefficients for some important gases a_1 to a_{16} are listed.

Table 3.1 Coefficients of the Enthalpy Calculation

	Nitrogen [N ₂]	Oxygen [O ₂]	Carbondioxide [CO ₂]	Water [H ₂ O] (gas)
a_1	0.3694063E+ 1	0.3721461E+ 1	0.2171539E+ 1	0.4159259E+ 1
a_2	-0.1334139E- 2	-0.2518398E- 2	0.1038499E- 1	-0.1725577E- 2
a_3	0.2652067E- 5	0.8589429E- 5	-0.1074106E- 4	0.5702012E- 5
a_4	-0.9775312E- 9	-0.8305377E- 8	0.6350127E- 8	-0.4596049E- 8
a_5	-0.9983837E- 13	0.2710013E- 11	-0.1629149E- 11	0.1424309E- 11
a_6	-0.1063539E+ 4	-0.1058373E+ 4	-0.4838467E+ 5	-0.3030886E+ 5
a_7	0.2289015E+ 1	0.3910662E+ 1	0.1067246E+ 2	-0.6866177
a_8	-0.9758881E+ 3	-0.9701834E+ 3	-0.9159472E+ 3	-0.1104501E+ 4
a_9	0.2856469E+ 1	0.3600001E+ 1	0.4415854E+ 1	0.2672525E+ 1
a_{10}	0.1598692E- 2	0.7819742E- 3	0.3194408E- 2	0.3033723E- 2
a_{11}	-0.6260775E- 6	-0.2240152E- 6	-0.1298684E- 5	-0.8540818E- 6
a_{12}	0.1132336E- 9	0.4251833E- 10	0.2416346E- 9	0.1179867E- 9
a_{13}	-0.7694805E- 14	-0.3348240E- 14	-0.1675410E- 13	-0.6201465E- 14
a_{14}	-0.8907648E+ 3	-0.1193583E+ 4	-0.4897651E+ 5	-0.2990882E+ 5
a_{15}	0.6394526E+ 1	0.3751753 E+ 1	-0.7292411	0.6888405E+ 1
a_{16}	-0.8031145E+ 3	-0.1105397E+ 4	-0.1507784E+ 4	-0.7044583E+ 3
M	28.0134 kg/kmol	31.9988 kg/kmol	44.0098 kg/kmol	18.0152 kg/kmol
ρ_n	1.2504 kg/m ³	1.4290 kg/m ³	1.9770 kg/m ³	0.8039 kg/m ³
R	0.29666 kJ/kg K	0.25958 kJ/kg K	0.18763 kJ/kg K	0.46144 kJ/kg K
σ	3.749 .10 ⁻¹⁰ m	3.541 .10 ⁻¹⁰ m	3.897 .10 ⁻¹⁰ m	2.520 .10 ⁻¹⁰ m
ϵ/k	79.80 K	88 K	213 K	775 K
δ	0.0 -	0.0 -	0.0 -	1.0 -
α	1.76 .10 ⁻³⁰ m ³	1.60 .10 ⁻³⁰ m ³	2.65 .10 ⁻³⁰ m ³	0.00 .10 ⁻³⁰ m ³

3.3 Mathematical Modelling of Trigeneration System

Software is designed for calculation of the combustion energy and the thermodynamic analysis of an engine, cogeneration and trigeneration system. Mathematical model depends on the inputs which fuel and air consumptions and flow rate. Also, for the power plant analysis electricity production, waste heat recovery boiler and heat exchanger's capacities are given by inputs.

Electrical efficiency of the internal combustion engine is calculated with equation below;

$$\eta_{engine,electrical} = \frac{\dot{W}_{electric}}{Combustion\ Energy} \quad (3.18)$$

Trigeneration system for heating thermodynamic analysis is calculated with equation below;

$$\eta_{Trigeneration,heating} = \frac{\dot{W}_{electric} + \dot{Q}_{WHRB} + \dot{Q}_{JW} + \dot{Q}_{AC} - W_{pumps}}{Combustion\ Energy} \quad (3.19)$$

Trigeneration thermodynamic analysis is calculated with equation below;

$$\eta_{Trigeneration,cooling} = \frac{\dot{W}_{electric} + \dot{Q}_{Abs.Chiller} + \dot{Q}_{AC} - W_{pumps}}{Combustion\ Energy} \quad (3.20)$$

For the calculation of the thermodynamic analysis; instead of combustion energy and heat recoveries, necessary work inputs like pumps are also exist in the equations. Power plant thermodynamic efficiency can be found by equations between 3.18-3.20.

CHAPTER FOUR

SOFTWARE OF THE COMBUSTION AND THE SYSTEM ANALYSIS

4.1 Introduction to Software

In this chapter, the operating principle of the program written for combustion and power plant analysis is explained. The program inputs, pseudo-code, algorithms and output are described.

An interface written in HTML (Hypertext Markup Language) posts the inputs to the main code, and runs with a program which is written in GOLANG, and displayed in an interface. Program has a struct based code which each gas is transported with its own information in a single struct and, it processes using the information needed during the calculations. The information about the gases is taken from the given sources and is written in code. These constants are used for thermophysical calculations.

There are two different packages under the main code. These packages calculate the thermophysical properties and the combustion for the gases which are coming from the main code.

4.2 Interface and Code Structure

4.2.1 Interface

Interface is written in HTML and run in localhost via web browser. In order to be able to adjust the combustion fuel – air ratio; there are fuel flow, fuel composition, air flow and air composition inputs inside the interface. Interface view for inputs is given in Figure 4.1. Results sections are not included in this view because of the reduce complexity. Results section is opened after clicking run button.

FUEL		Volumetric Flow [m ³ /h]		980
AIR		Air Flow [kg/saat]		22130
Combustion Composition				
			[m ³ /m ³]	
Methane	CH ₄			.9172
Ethane	C ₂ H ₆			.032
Propane	C ₃ H ₈			.0078
Buthane	C ₄ H ₁₀			.0036
Pentane	C ₅ H ₁₂			0
Carbondioxide	CO ₂			.0048
Nitrogen	N ₂			.0382
Air Composition				
			[kg/kg]	
Oxygen	O ₂			.234
Water	H ₂ O			.013
Nitrogen	N ₂			.753
Carbondioxide	CO ₂			0
Sulfurdioxide	SO ₂			0

Run

Figure 4.1 Software Interface

Design parameters are set in the opening page. Fuel gas design parameters are taken from MWM CG260-16 engine data sheet which is shown in Figure 4.2. There are two different errors and an error will be seen if the user tries to write fuel and air composition's summaries which are not written as equals one. Commonly used fuel gases like CH₄, C₂H₆, C₃H₈, C₄H₁₀ and C₅H₁₂ are taken as fuel composition components. N₂, CO₂ are also included in fuel composition components. Fuel flow and fuel composition inputs are given in Figure 4.3. Air composition is set to input values as in Figure 4.4.

Fuel gas data: 2)

Methane number:	[-]	81
Gas density:	[kg/Nm ³]	0,79
<small>Acc. to gas analysis</small>		
Analysis: CO ₂	[Vol%]	0,48
N ₂	[Vol%]	3,82
O ₂	[Vol%]	0,00
H ₂	[Vol%]	0,00
CO	[Vol%]	0,00
CH ₄	[Vol%]	91,14
C ₂ H ₄	[Vol%]	0,00
C ₂ H ₆	[Vol%]	3,20
C ₃ H ₆	[Vol%]	0,00
C ₃ H ₈	[Vol%]	0,78
C ₄ H ₈	[Vol%]	0,00
C ₄ H ₁₀	[Vol%]	0,36
C ₅ H ₁₂	[Vol%]	0,12
C _x H _y	[Vol%]	0,06
H ₂ S	[Vol%]	0,00

Figure 4.2 Fuel Consumption (MWM CG260-16 Engine Data Sheet)

Combustion Composition		[m ³ /m ³]
Methane	CH ₄	,9172
Ethane	C ₂ H ₆	,032
Propane	C ₃ H ₈	,0078
Buthane	C ₄ H ₁₀	,0036
Pentane	C ₅ H ₁₂	0
Carbondioxide	CO ₂	,0048
Nitrogen	N ₂	,0382

Figure 4.3 Fuel Parameters

Air Composition		[kg/kg]
Oxygen	O ₂	,234
Water	H ₂ O	,013
Nitrogen	N ₂	,753
Carbondioxide	CO ₂	0
Sulfurdioxide	SO ₂	0

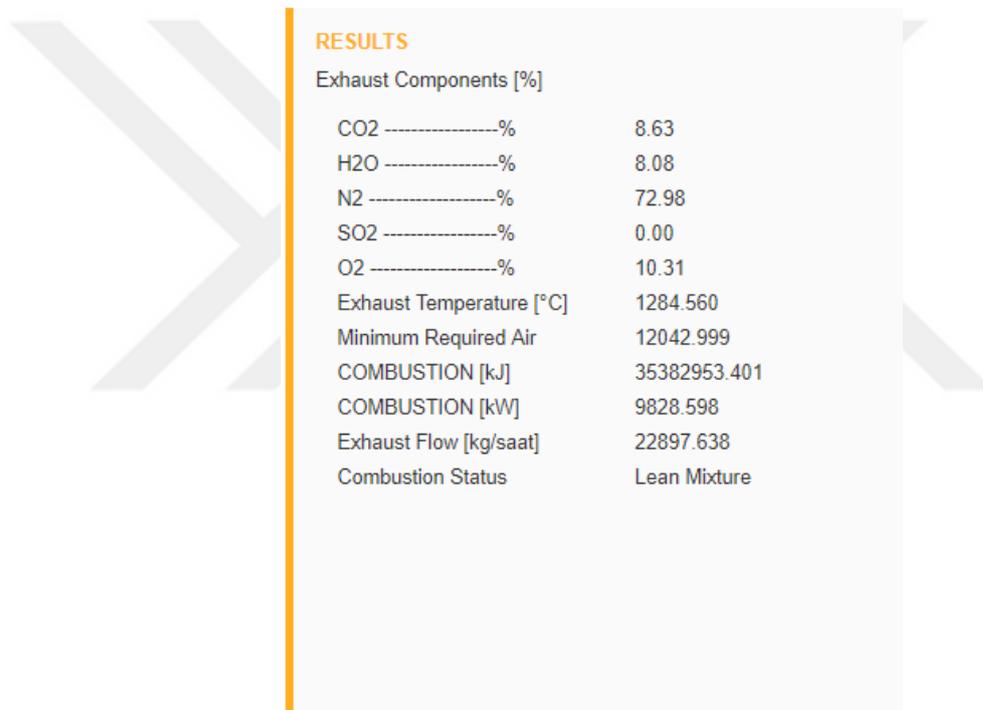
Figure 4.4 Air Parameters

Results section is opened after running the program. The program gives the following results:

- Exhaust components mass flow rate by percentage,
- Exhaust composition homogenization temperature,
- Minimum required air for stoichiometric combustion,
- Combustion output energy in kJ and kW,
- Exhaust flow rate by mass,

- Combustion status (rich mixture, stoichiometric, lean mixture). If mixture is rich, the program will not work. Rich mixture is not a common type of combustion and it is not desirable for combustion. To add a rich mixture calculation into the software, would take more memory and time for the combustion calculations. For this reason, this software designed only for the stoichiometric and lean mixtures combustions.

Results section shown in Figure 4.5. Total view after running the program is given in Figure 4.6.



The image shows a screenshot of a software interface with a light gray background and a large white box containing the results. The box has a vertical orange bar on the left side. The text inside the box is as follows:

RESULTS	
Exhaust Components [%]	
CO2 -----%	8.63
H2O -----%	8.08
N2 -----%	72.98
SO2 -----%	0.00
O2 -----%	10.31
Exhaust Temperature [°C]	1284.560
Minimum Required Air	12042.999
COMBUSTION [kJ]	35382953.401
COMBUSTION [kW]	9828.598
Exhaust Flow [kg/saat]	22897.638
Combustion Status	Lean Mixture

Figure 4.5 Combustion Results

← → C localhost:8080

FUEL

Volumetric Flow [m³/h]

Combustion Composition

	[m³/m³]	
Methane	CH4	<input type="text" value=",9172"/>
Ethane	C2H6	<input type="text" value=",032"/>
Propane	C3H8	<input type="text" value=",0078"/>
Butane	C4H10	<input type="text" value=",0036"/>
Pentane	C5H12	<input type="text" value="0"/>
Carbon dioxide	CO2	<input type="text" value=",0048"/>
Nitrogen	N2	<input type="text" value=",0382"/>

AIR

Air Flow [kg/seat]

Air Composition

	[kg/kg]	
Oxygen	O2	<input type="text" value=",234"/>
Water	H2O	<input type="text" value=",013"/>
Nitrogen	N2	<input type="text" value=",753"/>
Carbon dioxide	CO2	<input type="text" value="0"/>
Sulfur dioxide	SO2	<input type="text" value="0"/>

Run

RESULTS

Exhaust Components [%]	
CO2	8.63
H2O	8.08
N2	72.98
SO2	0.00
O2	10.31
Exhaust Temperature [°C]	1284.560
Minimum Required Air	12042.999
COMBUSTION [kJ]	35382563.401
COMBUSTION [kW]	9828.598
Exhaust Flow [kg/seat]	22897.638
Combustion Status	Lean Mixture

Trigeneration System Thermodynamic Analysis

Variables

Exhaust Flow	[kg/h]	22897.638	
Combustion Power	[kW]	9828.598	
Exhaust Before WHRB	[°C]	430.759	
Exhaust after WHRB	[°C]	123.420	
Electrical Output	[kW]		<input type="text" value="4300"/>
WHRB	[kW]		<input type="text" value="2210"/>
Chiller Capacity	[kW]		<input type="text" value="3023"/>
JW Heat Recovery	[kW]		<input type="text" value="1932"/>
AC Heat Recovery	[kW]		<input type="text" value="364"/>
Total Pumps Power	[kW]		<input type="text" value="153.5"/>

How Good!

RESULTS

$\eta_{\text{engine, electrical}}$	%	0.437
$\eta_{\text{trigeneration, heating}}$	%	0.871
$\eta_{\text{trigeneration, cooling}}$	%	0.727

Figure 4.6 Interface Total View

4.2.2 Code Structure

4.2.2.1 Java Script

Input datas has passing as ajax. After clicking run button, HTML posts ajax to main code. The taken inputs are posted like the code shown in Figure 4.7;

```
$.ajax({
  url: "/Combustion",
  method: "POST",
  data: {volFlow : volFlow,
        ch4 : ch4 ,
        c2h6 : c2h6 ,
        c3h8 : c3h8 ,
        c4h10 : c4h10 ,
        c5h12 : c5h12 ,
        co2 : co2,
        n2 : n2,
        airkgFlow : airkgFlow ,
        airO2 : airO2,
        airH2O : airH2O,
        airN2 : airN2,
        airCO2 : airCO2,
        airSO2 : airSO2,
        whrbOut : whrbOut,
        jwOut : jwOut,
        acOut : acOut,
        elecOut : elecOut
      },
  },
```

Figure 4.7 Post Method

4.2.2.2 Thermophysical Properties Package

Coefficients are used for the enthalpy calculation as in the Table 3.1. We use the package which has written to calculate enthalpy for a single gas by using the temperature and also calculate mixture enthalpy by using the temperature.

Inside the package there is also a mixture temperature for different gases enthalpies and temperatures. Mixture temperature can be found with an iteration which takes first value of temperature 10 °C and tries to converge to the mixture temperature. Package uses different coefficients for 10 - 1000 K and 1000 - 5000 K ranges. Enthalpy calculation can be given as a code shown in Figure 4.8.

```

func (gas *Gas) Enthalpy(temp float64) float64 {
    h := 0.0
    if temp <= 1000 {
        h = gas.gasConstant * temp * (gas.A[0] + gas.A[1]/2*temp + gas.A[2]/3*math.Pow(temp, 2)
        + gas.A[3]/4*math.Pow(temp, 3) + gas.A[4]/5*math.Pow(temp, 4) + gas.A[7]/temp)
    } else {
        h = gas.gasConstant * temp * (gas.A[8] + gas.A[9]/2*temp + gas.A[10]/3*math.Pow(temp, 2)
        + gas.A[11]/4*math.Pow(temp, 3) + gas.A[12]/5*math.Pow(temp, 4) + gas.A[15]/temp)
    }
    return h
}

```

Figure 4.8 Partial Code of an Enthalpy Calculation

Enthalpy of mixture is calculated by an array called “comp” and all of the composition components solved one by one with an array inside the “Mix_Enthalpy” function. Then, “Mix_TempEnthalpy” function uses this mixture enthalpy for calculation the mixture temperature. Enthalpy of mixture calculation can be given as a code is shown in Figure 4.9

```

func Mix_Enthalpy(comp []float64, temp float64) float64 {
    mixEnt := comp[0]*CarbonDioxide.Enthalpy(temp) + comp[1]*SulfurDioxide.Enthalpy(temp) +
    comp[2]*Nitrogen.Enthalpy(temp) + comp[3]*Oxygen.Enthalpy(temp) + comp[4]*WaterAsGas.Enthalpy(temp)
    return mixEnt
}

```

Figure 4.9 Code of Mixture Enthalpy Calculation

Homogenization temperature of mixture can be calculated as the code is shown in Figure 4.10

```

func Mix_TempEnthalpy(comp []float64, enth float64, times int) float64 {
    tCal := 4723.15
    enth10 := Mix_Enthalpy(comp, 283.15)
    enthCal := Mix_Enthalpy(comp, 4723.15)
    if enth < enthCal {
        for i := 1; i < times; i++ {
            enthCal = Mix_Enthalpy(comp, tCal)
            tCal = tCal - (enthCal-enth)*(tCal-283.15)/(enthCal-enth10)
        }
    } else {
        fmt.Println("Energy Output:", enthCal, "greater than enthalpy at 4500", enth)
        return -1.0
    }
    return tCal
}

```

Figure 4.10 Partial Code to Find Homogenization Temperature of Mixture

4.3 Governing Approaches and Limits

Software is written within certain limits. The reasons for these limits are mainly; shortening the response time of the program and the limit values of the equations. To reduce the response time of the program, the program does not produce results for rich mixtures. Rich mixtures are undesirable mixtures in any combustion application. Since not all the fuels are burned, it causes the unburnt fuel to be blown into the atmosphere. To burn rich mixtures, the program needs extra processing, which causes longer response time. The flow chart of the written code is given in Figure 4.11.

On the other hand, the coefficients used in enthalpy calculation has limits up to 5000 K. This temperature limit is useful to burn a common mixture. However, with decreasing air flow rate, temperature increased upper this limit, in that case program gives result as "Temperature Limit Exceeded".

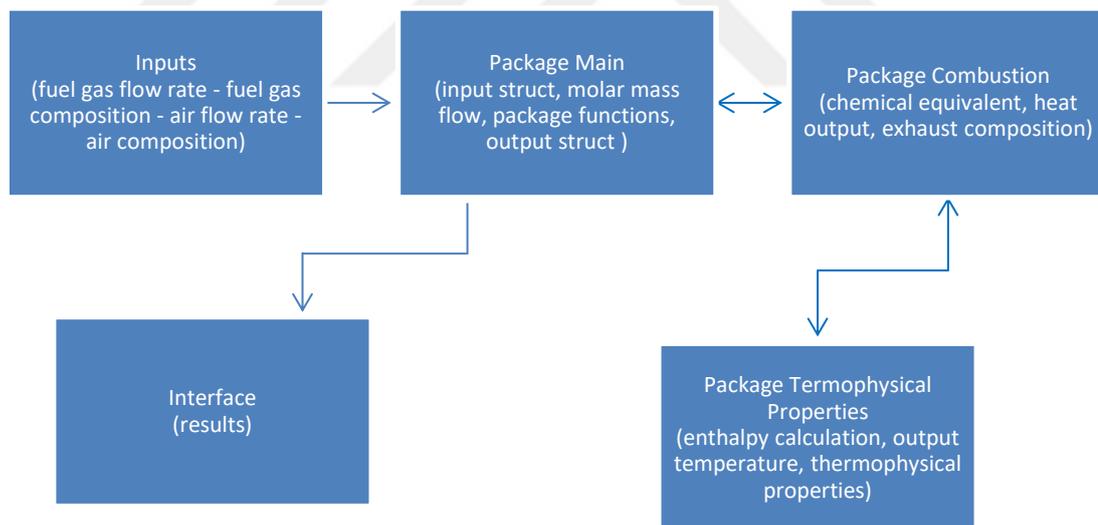


Figure 4.11 The Schematics of the Code Structure

CHAPTER FIVE

CASE STUDY

5.1 Hospital Application

In this section, trigeneration system in a hospital in Ankara has been introduced. As system input; fuel composition, air flow, air composition, waste heat boiler output, heat exchanger capacity, chiller capacity and pump power are taken. Firstly, the combustion energy calculated in the gas engine and the system outputs and the system efficiency are found.

Four sets of MWM CG260-16 4300 kW_e natural gas fired engines supply the electricity requirement of the hospital. General heating requirement of the hospital is 62500 kW and cooling requirement of the hospital is 50 MW.

5.2 Working Principle of Trigeneration Power Plant

Trigeneration system is crucial for the facilities like hospitals, factories, shopping malls etc. because of uninterrupted electricity production. Also, systems efficiencies are very high like up to 85%. Main purpose of the system is heat recovery. Without heat recovery, only electricity production is not enough to raise the system efficiency.

In our system there are different kinds of heat recovery circuits like; jacket water (JW), after cooler (AC), oil cooling (lube oil) and exhaust circuits. In addition, system has its own security chain to protect gas engine from overheating. Automatization exists for both the protection and efficient heat recovery. Thermocouples give temperature knowledge to the main board and the system controls the flows for the most efficient heat recovery or security.

System working principle and piping and instrumentation diagram is given in Figure 5.1.

5.3 System Elements

Trigeneration system flow diagram is shown in Figure 5.1. As one can see, there are heat recovery equipment, automatization equipment, measurements etc. Under this title, information about these elements will be given. System 3D CAD drawing is shown in Figure 5.2.

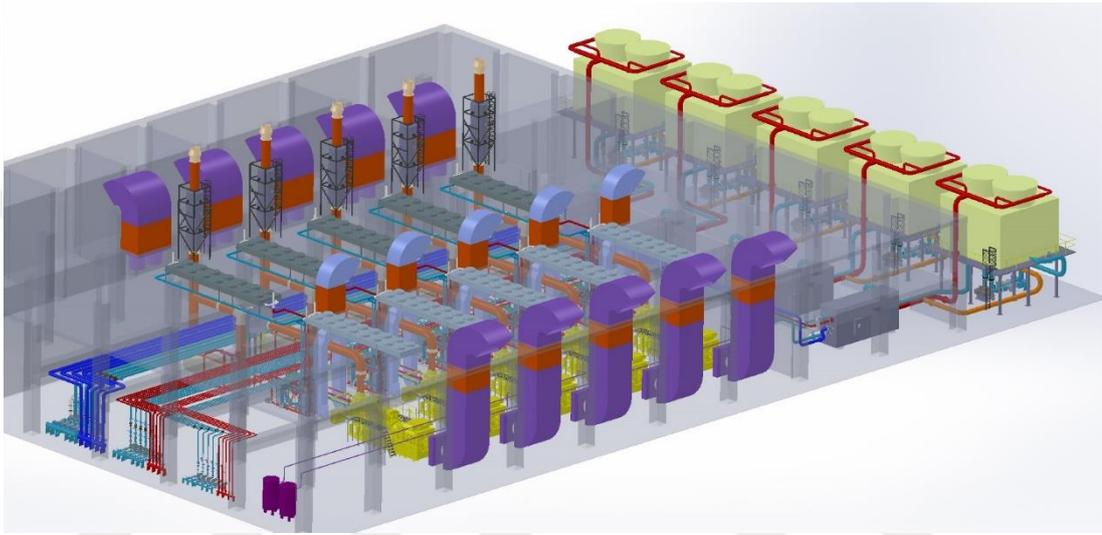


Figure 5.2 Power Plant 3D View

5.3.1 Gas Engine

There are 4 groups of MWM CG260-16 natural gas fired engines which are used in this system. Totally 17.2 MW electricity production is enough to feed the hospital's electricity requirement. Gas engine data sheet is given in Figure 5.4.

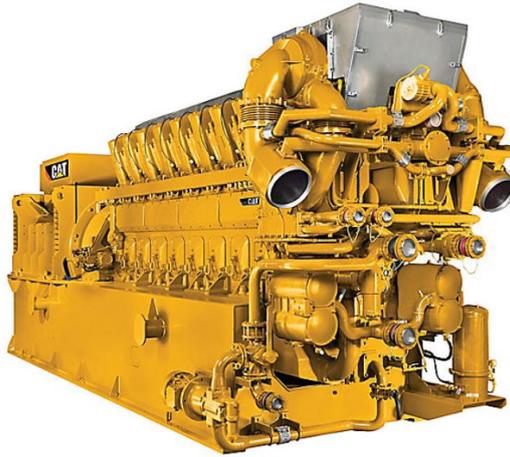


Figure 5.3 MWM CG260-16 Gas Engine (MWM, 2018)

4300 kWel; 11000 V, 50 Hz; Acc. to gas analysis

Design conditions				Fuel gas data: ²⁾	
Comb. air temperature / rel. Humidity:	[°C] / [%]	25 / 70		Methane number:	[-] 81
Altitude:	[m]	870		Gas density:	[kg/Nm ³] 0,79
Exhaust temp. after heat exchanger:	[°C]	120		Acc. to gas analysis	
NO _x Emission (tolerance - 8%):	[mg/Nm ³ @5%O ₂]	500		Analysis: CO ₂	[Vol%] 0,48
Genset:				N ₂	[Vol%] 3,82
Engine:	CG260-16			O ₂	[Vol%] 0,00
Speed:	[1/min]	1000		H ₂	[Vol%] 0,00
Configuration / number of cylinders:	[-]	V / 16		CO	[Vol%] 0,00
Bore / Stroke / Displacement:	[mm]/[mm]/[dm ³]	260 / 320 / 272		CH ₄	[Vol%] 91,14
Compression ratio:	[-]	12,0		C ₂ H ₄	[Vol%] 0,00
Mean piston speed:	[m/s]	10,7		C ₂ H ₆	[Vol%] 3,20
Mean lube oil consumption at full load:	[g/kWh]	0,3		C ₃ H ₆	[Vol%] 0,00
Engine-management-system:	[-]	TEM EVO		C ₃ H ₈	[Vol%] 0,78
Generator:	Marelli MJH 800 MC6			C ₄ H ₆	[Vol%] 0,00
Voltage / voltage range / cos Phi:	[V] / [%] / [-]	11000 / ±10 / 1		C ₄ H ₁₀	[Vol%] 0,36
Speed / frequency:	[1/min] / [Hz]	1000 / 50		C ₄ H ₁₂	[Vol%] 0,12
				C ₂ H ₂	[Vol%] 0,06
				H ₂ S	[Vol%] 0,00
Energy balance					
Load:	[%]	100	75	50	
Electrical power COP acc. ISO 8528-1:	[kW]	4300	3225	2150	
Engine jacket water heat:	[kW ±8%]	1458	1084	752	
Intercooler LT heat:	[kW ±8%]	364	259	168	
Lube oil heat:	[kW ±8%]	474	395	341	
Exhaust heat with temp. after heat exchanger:	[kW ±8%]	2309	1912	1468	
Exhaust temperature:	[°C]	450	477	507	
Exhaust mass flow, wet:	[kg/h]	22898	17447	12304	
Combustion mass air flow:	[kg/h]	22130	16850	11874	
Radiation heat engine / generator:	[kW ±8%]	212 / 94	207 / 82	203 / 73	
Fuel consumption:	[kW+5%]	9840	7642	5495	
Electrical / thermal efficiency:	[%]	43,7 / 43,1	42,2 / 44,4	39,1 / 46,6	
Total efficiency:	[%]	86,8	86,6	85,7	

Figure 5.4 Gas Engine Data Sheet (MWM CG260-16)

5.3.2 Waste Heat Recovery Boiler

Waste heat recovery capacity for full-load, which is given in Figure 5.4 (engine data sheet), is 2309 kW. WHRB (Waste Heat Recovery Boiler) capacity has calculated 2210 kW regarding design parameters. Exhaust gas inlet temperature to boiler is 450 °C and the flow rate is 22898 kg/h. JW is using for pre-heating heat exchanger for the

hot water boiler. Hot water returns from the hospital side at 71 °C, and heats to 82.1 °C in JW heat exchanger. After that, it increases 95 °C inside the hot water boiler. For each engine set in full-load; 154 m³/h, 95 °C hot water goes for heating the hospital. Heating or cooling collectors are shown in Figure 5.5.

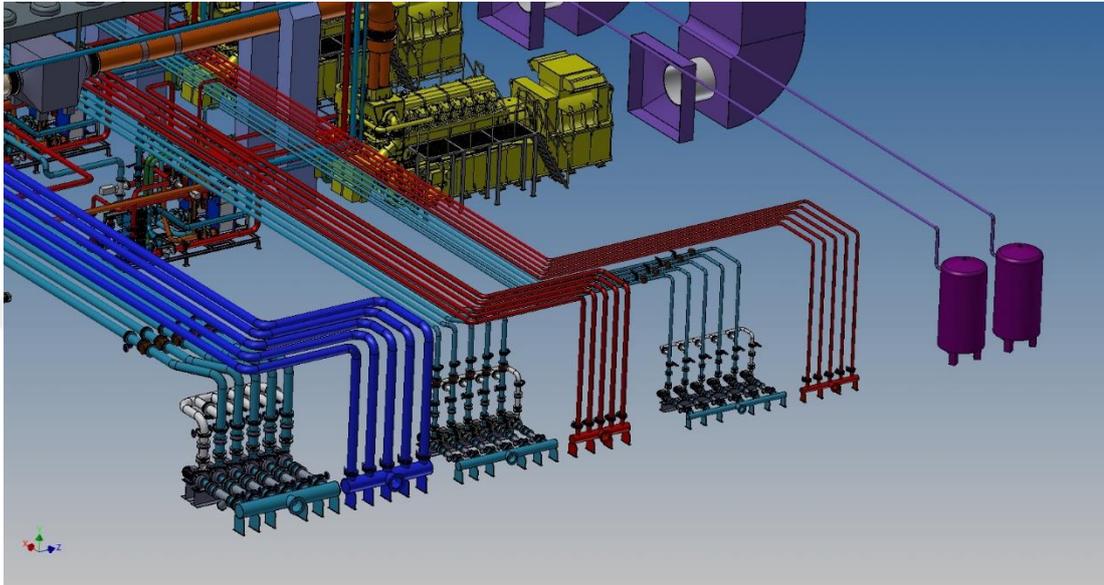


Figure 5.5 Heating and Cooling Collectors

5.3.3 Heat Exchangers

Engine cooling systems has 37% glycol ethylene – water mixture for antifreeze. Thus, the lines are not desired to be kept very long. Heat is transferred to the water lines by using heat exchangers. Pump skid group and heat exchangers are shown in Figure 5.6.

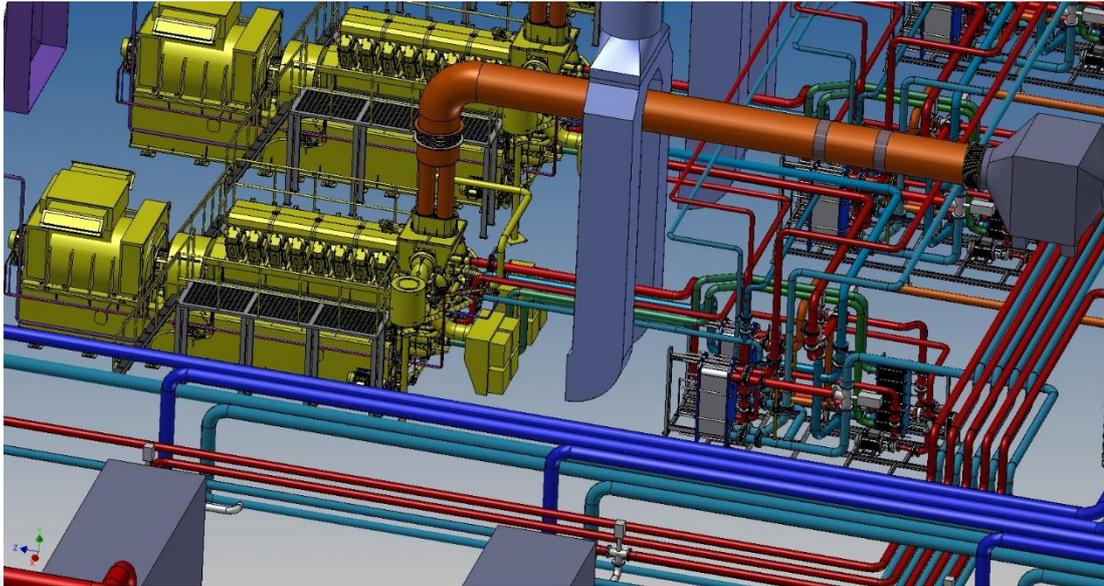


Figure 5.6 Heat Exchangers, Pump Skid Group

5.3.4 Absorption Chiller

Wu, Wang (2006), adsorption-cooling technology is a novel, environmentally friendly and effective means of using low-grade heat sources. An adsorption refrigeration system is similar to vapor compression systems except that heat instead of work provides the energy needed for compression. Unlike conventional vapor compression systems which require a mechanical compressor assembly, this new technology uses a thermally driven static sorption bed, saving as much as 90% of the required input power typically used to drive a mechanical compressor.

The functioning of the basic cycle of adsorption cooling can be presented as comprising four phases and described as below;

1. A heating-pressurization, during which the absorber is isolated from both the condenser and the evaporator. The pressure inside the absorber then increases until reaching the condensation pressure, thanks to the heat supplied by an external heat source.

2. An isobaric condensation, during which the absorber is connected to the condenser, allowing the refrigerant vapor to flow the absorber to the condenser and condenses therein as the heating is still continuing. This simultaneity of heating and

vapor flow and condensation makes the process isobaric. The condensation heat is absorbed by the cooling medium or could be used to provide heating if the purpose of the system is heat pumping. The condensate is then expanded and drained into evaporator at lower pressure.

3. A cooling-depressurisation, during which the absorber is isolated from both the condenser and the evaporator. The absorber is cooled down and the pressure decreases back to the value of adsorption condition.

4. An isobaric absorption, during which the absorber is connected to the evaporator and isolated from condenser. The low-pressure liquid water contained in the evaporator is evaporated by extracting latent heat of evaporation from the space when being cooled down, and, simultaneously, the evaporated vapor is adsorbed anew by the reactivated adsorbent contained in the absorber.

Working principle of an absorption chiller is shown in Figure 5.7. Absorption chillers and cooling towers in power plant is shown in Figure 5.8.

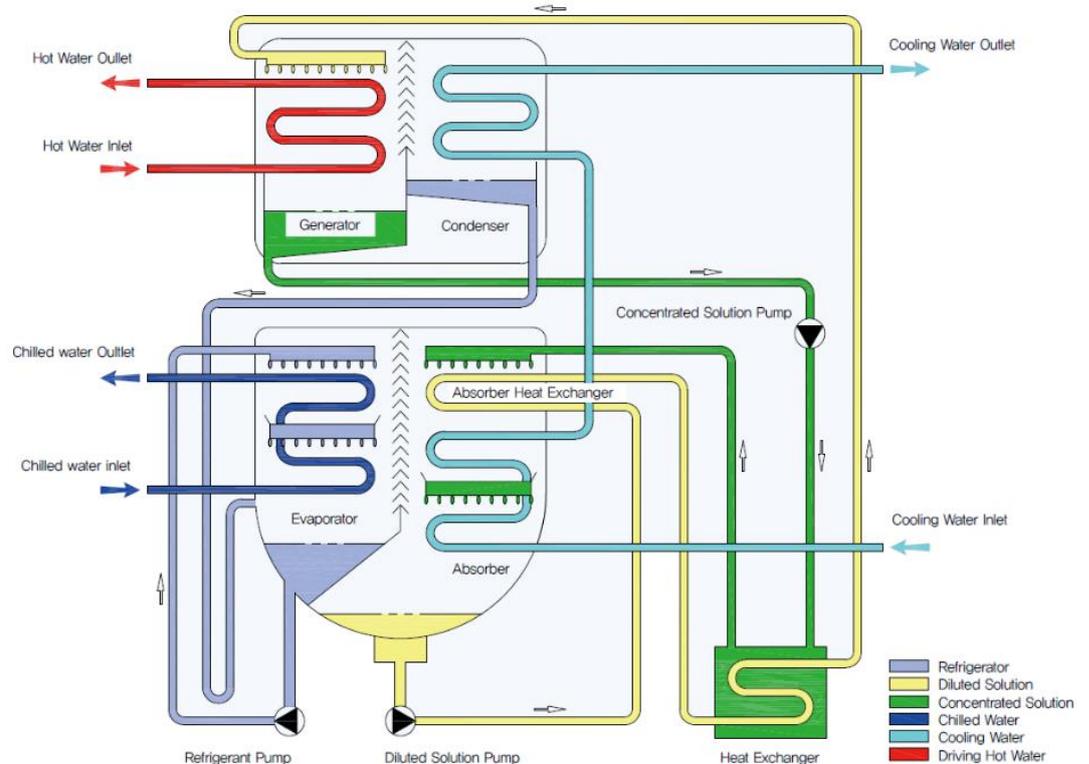


Figure 5.7 Working Principle of an absorption Chiller (Goldman, 2018)

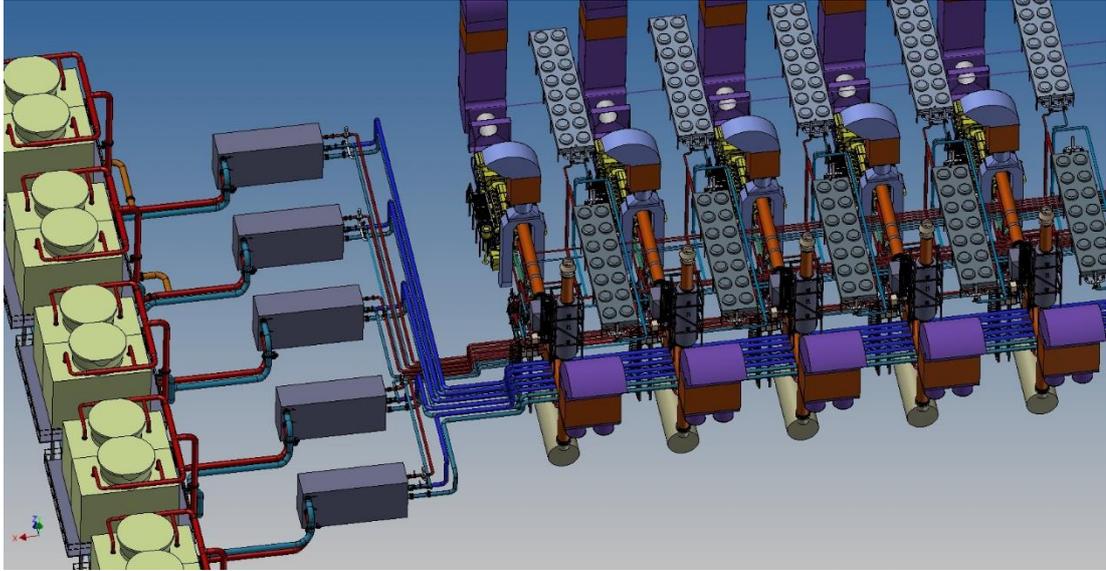


Figure 5.8 Absorption Chillers and Cooling Towers

5.4 Piping and Instrumentation

Piping and instrumentation diagram provides information on the equipment required for the system to operate and placements of the equipment. The installation of the system should be done in accordance with the order in the flow diagram. Equipment placement and automation are important for adequate cooling of the engine and for heat recovery

5.4.1 Automation

The most important criteria for the automatization is engine protection. There are different scenarios for the system works. These are like heat recovery, start-up and overheating scenarios. First reaction of overheating situation is always opening the three-way valve of the exhaust line. This provides flow of the exhaust to direct atmosphere. At this moment waste heat recovery boiler capacity is starts to decrease.

5.4.2 Start-up, Simple Cycle and Overheating

5.4.2.1 Start-up

At the first start-up, engine needs to warm up. This condition is not takes too much time. In this cycle automatization is set to short cycle of the coolant mixture. All of the three-way valves of the coolant circuits are working for short circuits. Then three-way valves are opening percentage for the temperature knowledge coming from the thermocouples. Setting system to working temperatures.

Engine coolant circuits and three-way valves are shown in Figure 5.9.

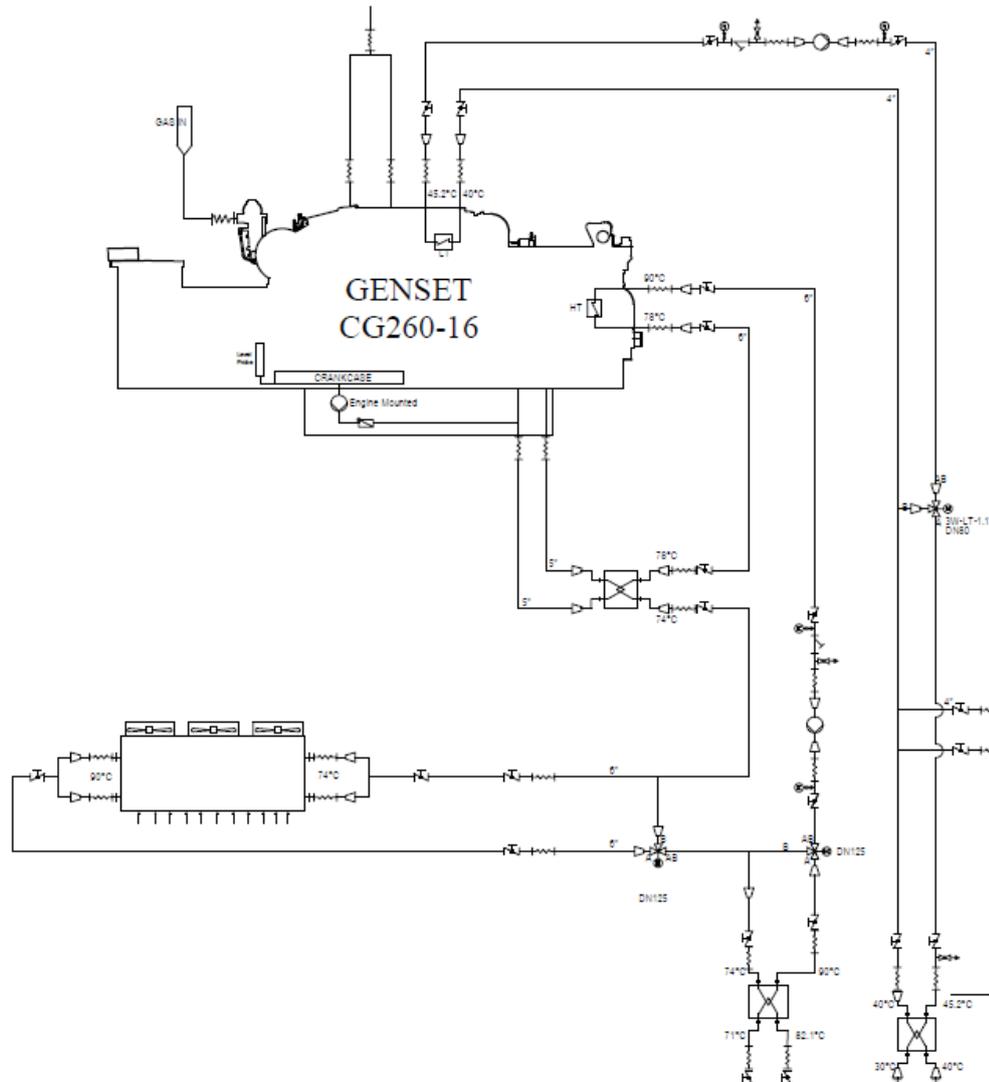


Figure 5.9 Engine Coolant Circuits

5.4.2.2 Simple Cycle

Simple cycle means that only electricity production is done by the system. In this cycle engine cools with dry cooling system. System efficiency is highly decreases in this cycle.

5.4.2.3 Overheating

Overheating is unwanted scenario for the system. It can be effect shut down the engine and also under some circumstance permanent damage to the engine. To avoid this situation, security equipment like three-way valves permanently cuts to the flow. And dry cooling system steps in for the case of over-heating situations.

5.5 Heating and Cooling Circuits

There are two different heat recovery modes in this trigeneration system and depending on the demands of the hospital, the system works in either cooling or heating cycles. The working principles of the heating and cooling cycles are identical; however, the heat transfer takes place between absorption chiller or the heat exchanger for the cooling and heating cycles, respectively.

5.5.1 Heating Circuit

For the heating cycle, the system supplies the recovered heat through the hospital via a heat exchanger. System flow diagram is shown in Figure 5.1, before heat exchanger JW heat as pre-heating of the boiler and boiler heat combined to transfer to their heat to the heat exchanger. Hospital gained heating from the HW heat exchanger, AC heat exchanger are shown in Figure 5.1.

5.5.2 Cooling Circuit

For the cooling cycle, systems end with an absorption chiller. System flow diagram shown in Figure 5.1, before absorption chiller JW heat as pre-heating of the boiler and

boiler heat combined to transfer to their heat to the absorption chiller. Hospital gained cooling from the absorption chiller and heating from AC heat exchanger are shown in Figure 5.1.



CHAPTER SIX

RESULTS AND DISSCUSSION

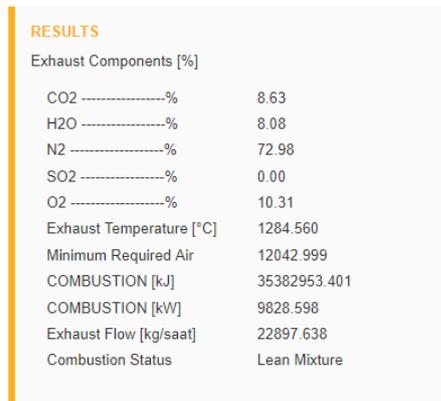
6.1 Results

In this chapter, results of the thermodynamic analysis are given. Results calculated by design parameters for 100%, 75% and 50% capacities of gas engine.

6.1.1 Combustion

Combustion energy calculated by formation enthalpies via natural gas flow rate, gas consumption, air flow rate and air consumption. Software generates chemical equations of combustion in molar mass flow. Equalize the equations and generating exhaust flow rate and the exhaust flow consumption by an input values. Combustion energy finds in kJ, for the efficiency calculations converted to power as kW. For each capacities combustion power is calculated like below;

For 100% capacity combustion energy calculation is shown in Figure 6.1.



RESULTS	
Exhaust Components [%]	
CO2 -----%	8.63
H2O -----%	8.08
N2 -----%	72.98
SO2 -----%	0.00
O2 -----%	10.31
Exhaust Temperature [°C]	1284.560
Minimum Required Air	12042.999
COMBUSTION [kJ]	35382953.401
COMBUSTION [kW]	9828.598
Exhaust Flow [kg/saat]	22897.638
Combustion Status	Lean Mixture

Figure 6.1 Results of the Combustion of the 100% Capacity

In 100% capacity, total heat output of the combustion chamber calculated as 35382.95 MJ.

For 75% capacity combustion energy calculation is shown in Figure 6.2.

RESULTS	
Exhaust Components [%]	
CO2 -----%	9.04
H2O -----%	8.41
N2 -----%	72.87
SO2 -----%	0.00
O2 -----%	9.69
Exhaust Temperature [°C]	1334.223
Minimum Required Air	9339.468
COMBUSTION [kJ]	27439841.413
COMBUSTION [kW]	7622.178
Exhaust Flow [kg/saat]	16955.311
Combustion Status	Lean Mixture

Figure 6.2 Results of the Combustion of the 75% Capacity

In 75% capacity, total heat output of the combustion chamber calculated as 27439841.4 kJ.

For 50% capacity combustion energy calculation is shown in Figure 6.3.

RESULTS	
Exhaust Components [%]	
CO2 -----%	9.98
H2O -----%	9.15
N2 -----%	72.62
SO2 -----%	0.00
O2 -----%	8.26
Exhaust Temperature [°C]	1446.573
Minimum Required Air	6758.826
COMBUSTION [kJ]	19857779.970
COMBUSTION [kW]	5516.050
Exhaust Flow [kg/saat]	11110.817
Combustion Status	Lean Mixture

Figure 6.3 Results of the Combustion of the 50% Capacity

In 50% capacity, total heat output of the combustion chamber calculated as 19857779.9 kJ.

6.1.2 Heat Recovery

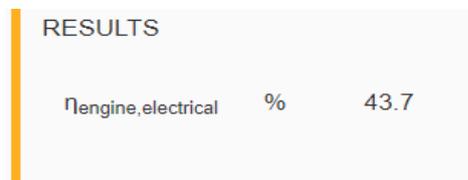
Heat recovery values is taken from design parameters, only engine efficiencies can calculate from input values. Because of the system didn't commissioned yet, waste heat recovery boiler's capacity for each capacity didn't seen.

Engine side heat recoveries in JW, AC, LubOil is taken from engine data sheet is given Figure 5.4 for the exhaust temperature calculation via software.

6.2 Gas Engine Efficiency

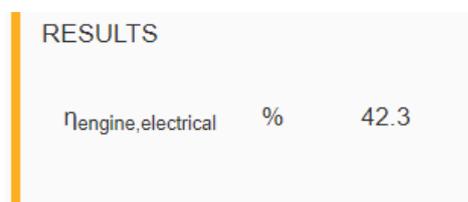
For the calculation of the combustion energy, inputs are taken from an engine data sheet is shown in Figure 4.4. Considering each capacity (100%, 75%, 50%) electrical efficiencies are compared. Engine electrical efficiency calculated by Equation 3.18.

Engine electrical efficiencies that are evaluated for each capacity are shown in Figures 6.4 to 6.6.



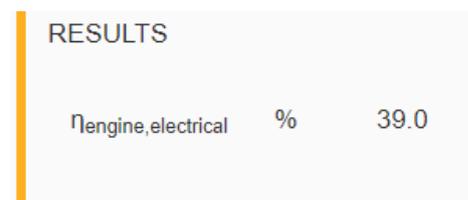
RESULTS		
$\eta_{\text{engine,electrical}}$	%	43.7

Figure 6.4 Gas Engine Electrical Efficiency for a 100% capacity



RESULTS		
$\eta_{\text{engine,electrical}}$	%	42.3

Figure 6.5 Gas Engine Electrical Efficiency for a 75% capacity



RESULTS		
$\eta_{\text{engine,electrical}}$	%	39.0

Figure 6.6 Gas Engine Electrical Efficiency for a 50% capacity

Gas engine electrical efficiency is inversely proportional to electricity generation. Engine electrical efficiency decreased with a fuel flow rate rise.

6.3 Trigeneration System for Heating Efficiency

Trigeneration system efficiency for heating calculated with, waste heat recoveries for only heating and electricity production. In our system there are three different heat recoveries exists; JW, AC, and waste heat recovery boiler.

Trigeneration system efficiency calculated with Equation 3.19. Calculation of the efficiency for 100% load is given below;

$$\eta_{Trigeneration,heating} = \frac{Electricity\ Production + W_{HRB} + JW + AC - W_{pumps}}{Combustion\ Energy} \quad (3.19)$$

$$\eta_{Trigeneration,heating} = 0.871$$

Trigeneration system heating efficiency for 100% load is 87.1% is calculated. Results of the program is shown in Figure 6.7.

RESULTS		
$\eta_{engine,electrical}$	%	43.7
$\eta_{trigeneration,heating}$	%	87.1

Figure 6.7 Trigeneration Efficiency for Heating Results

6.4 Trigeneration System for Cooling Efficiency

Trigeneration system efficiency for cooling calculated with, absorption chiller, engine AC cooling system and electricity production. In this case, the thermal energy that is extracted from the waste heat recovery boiler and JW is supplied through the

absorption chiller, on the other hand, the heat recovered from the AC is used only partial heating. As the working temperature of the AC systems stand between 40 – 45.2°C temperatures, it is commonly used for lavatories and showers.

Trigeneration system efficiency for cooling is calculated by Equation 3.20. Calculation of the efficiency for 100% load is given below;

$$\eta_{Trigeneration,cooling} = \frac{Electricity\ Production + Abs.Chiller + AC - W_{pumps}}{Combustion\ Energy} \quad (3.20)$$

$$\eta_{Trigeneration,heating} = 0.764$$

Trigeneration system cooling efficiency for 100% load is 76.4% is calculated. Results of the program is shown in Figure 6.8.

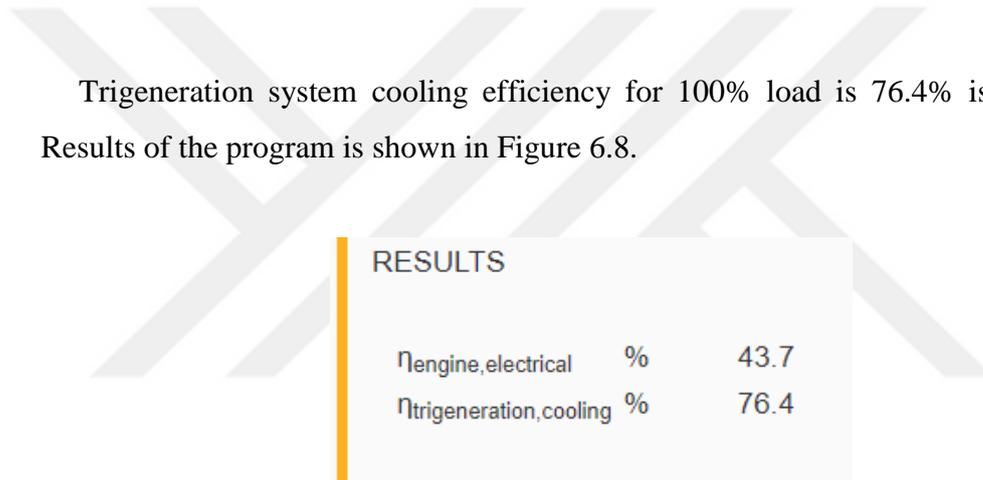


Figure 6.8 Trigeneration Efficiency for Cooling Results

6.5 Results Comparing

According to engine data sheet in Figure 5.4, electrical efficiencies are given for each capacity. Comparison between data sheet values and the results is given in Table 6.1.

Table 6.1 Gas Engine Electrical Efficiencies for the Data Sheet and the Results

Gas engine electrical efficiencies [%]		
	Engine Data Sheet	Results
100% Load	43.7	43.7
75% Load	42.2	42.3
50% Load	39.1	39

Considering results of the calculations, engine efficiencies of the engine data sheets and the results of the software are almost same. Differences between data sheet values and the calculations are maximum point one in a hundred percent.

System efficiencies for the cogeneration and the trigeneration in 100% load is calculated with equations 3.19 – 3.20. According to these calculations, results of 100% load is given in Figure 6.9.

RESULTS		
$\eta_{\text{engine,electrical}}$	%	43.7
$\eta_{\text{trigeneration,heating}}$	%	87.1
$\eta_{\text{trigeneration,cooling}}$	%	76.4

Figure 6.9 Efficiencies for 100% Load

Considering results in Figure 6.9, cogeneration efficiency is higher than trigeneration efficiency. Main reason of the differences between efficiencies is absorption chiller. Absorption chillers efficiencies are less than heat exchangers. For this reason, heating case is more efficient.

Figure 6.10 shows that the effects of engine load capacity on the first law efficiency of the system. The results show that as the load capacity increases, the electrical efficiency increases. This results mainly due to the fact that when the load capacity increases, more power produced by the generator. Thus, the efficiency increases. When the load capacity is 100%, the efficiency gets its maximum value as the 43.7%.

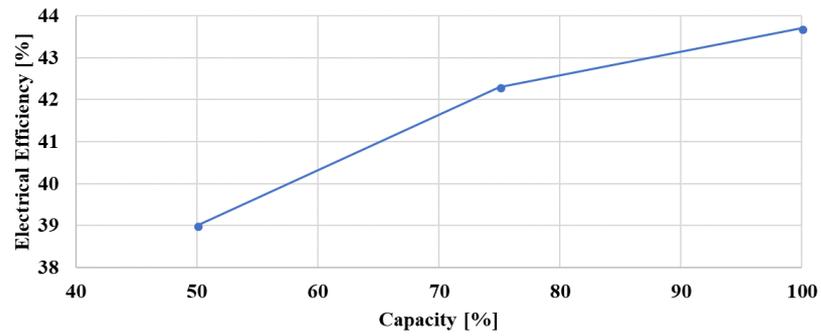


Figure 6.10 Effect of the Engine Load Capacity on the Engine Efficiency

Figure 6.11 shows that the effects of cycle type which are only electrical production (simple cycle), electrical and heating (cogeneration) and electrical, heating and cooling (trigeneration cycle) on the overall efficiency of the system. The results obtained when cogeneration cycle is used, the system efficiency has maximum value (87.1%).

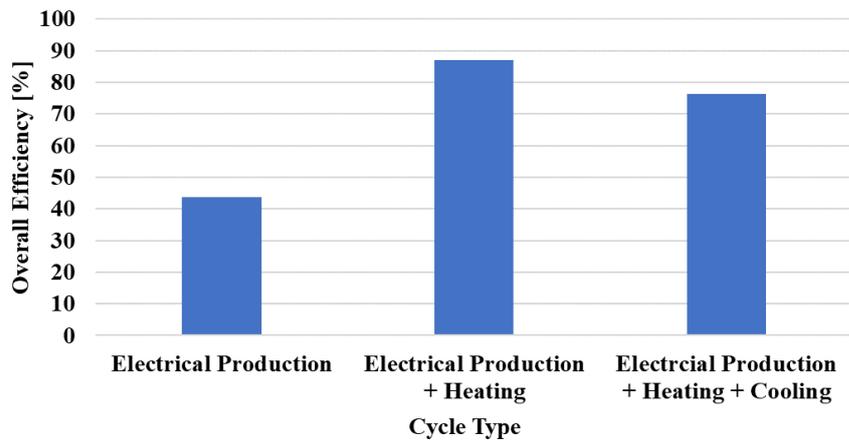


Figure 6.11 Effect of the Cycle Type on the Overall System Efficiency

CHAPTER SEVEN

CONCLUSION

7.1 Conclusions

In this study, trigeneration system efficiency depend on the fuel gas flow rate of the gas engine were investigated. Gas engine efficiency by the electricity production and combustion energy are shown. The following conclusions were obtained in summary;

- One of the aim of this study is creating a web-based software to calculate cogeneration or trigeneration power plant for end-users.
- The advantage of the program is that it can compute without interfering with the code. In this case, software can be used for the systems which generates electricity by a combustion energy such as fuel gas fired turbine, generator systems and so on.
- Differences between other calculation programs are having simple interface for giving inputs and calculating for different cases.
- For the future works it can be used for additional combustion for the duct firing boilers or waste heat recovery boilers, it gives output values of the exhaust properties.

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