

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**SIMULATION OF ORGANIC RANKINE CYCLE MODULE IN
SCHARNHAUSER PARK CHP PLANT**

**MSc. Thesis by
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**SCHARNHAUSER PARK KOMBİNE ISI VE ENERJİ SANTRALİNDE BULUNAN
ORGANİK RANKİNE DÖNGÜSÜNÜN SİMÜLASYONU**

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FOREWORD

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Chemical Engineering

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ABBREVIATIONS

ACSL	: Advanced Continuous Simulation Language
BFB	: Bubbling Fluidized Bed
CFB	: Circulating Fluidized Bed
CHP	: Combined Heat and Power
CV_i	: Calorific Value of Component i
d.b	: Dry Basis
DAE	: Differential Algebraic Equation
DIMAP	: Digital Modular Avionics Program
ESMS	: Electronic Soccer Management Simulator
ESS	: Engineering Equation Solver
FBC	: Fluidized Bed Combustion
GHG	: Green House Gases
GT Pro	: Gas Turbine Simulation Program
GVC	: Gross Calorific Value
HfT	: Hochschule fuer Technik
h_i	: Enthalpy of Component i
HYSYS	: Hydrotech System
ICAS	: Interacademic Commission for Alpine Studies
IEA	: International Energy Agent
IPSEpro	: Integrated Process Simulation Environment Professional
MDK	: Model Development Kit
MDM	: Silicon Oil
m_i	: Mass Flow Rate of Component i
M_i	: Molecular Weight of Component i
MSW	: Municipal Solid Waste
NCV	: Net Calorific Value
NO_x	: Nitrogen Oxide
ODE	: Ordinary Differential Equation
OMTS	: Octamethyltrisiloxane
ORC	: Organic Rankine Cycle
P	: Pressure
PCDD	: Polychlorinated Dibenzodioxins
PCDF	: Polychlorinated Dibenzofurans
P_{el}	: Power Generation
PSE	: Process Simulation Environment
Q	: Heat Energy
R123	: 2,2-Dichloro-1,1,1-Trifluoroethane
REN21	: Renewable Energy Policy Network for the 21 st Century
RPM	: Revolutions per Minute
S	: Entropy
SENCE	: Sustainable Energy Components
SO_x	: Sulphur Oxides
T	: Temperature

W : Work
w.b : Wet Basis
waf : Wet Ash Free Fuel
X_i : Weight Percentage of Component i

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SIMULATION OF ORGANIC RANKINE CYCLE MODULE IN SCHARNHAUSER PARK CHP PLANT

SUMMARY

Energy demand in the world has sharply gone up for last 50 years and this increase is expected to increase in the future. Bioenergy has become an important alternative energy like other renewable energies due to limitation of energy reserve and environmental problems. Although traditional biomass such as cooking and heating has been utilized for energy generation since the beginning of civilization, usage of modern biomass has increased with energy crisis. Even if efficiency of electricity from biomass is lower than from fossil fuel, bioenergy became one of the profitable options for electricity generation. Waste biomass such as agricultural, forested and municipal waste or converted biofuel from this biomass is used as fuel in most biomass power plants. Combined Heat Power (CHP) or cogeneration technology is preferred for electricity production with less efficiency such as from waste biomass. Because of simultaneous electricity and useful heat production, power generation can be more effective with this technology. Moreover, hence more energy can be produced with less fuel; CHP allows lower CO₂ emissions to the environment. Usage of Organic Rankine Cycle (ORC) is effective option for power generation from biomass in medium or small scale CHP plants. Organic liquid is utilized as working medium in ORC instead of water as Rankine Cycle. This enables exploiting efficiently low temperature heat sources to produce electricity. Many biomass fired CHP plants based on ORC module exist in all over the world. The energy supply system of the Scharnhauser Park CHP plant in Stuttgart, Germany is a practical example of the utilization of the ORC Technology in biomass fired CHP plant. In this plant, natural wood scraps and forested wood are burned for electricity and heat generation. Produced heat is used for heating district system. In this study, a simulation program of ORC module of CHP plant in Scharnhauser Park is presented and IPSEpro is used as software package. Twenty eight data groups, which were taken from the Scharnhauser Park CHP plant, were utilized for simulation. These data include properties of thermal oil, turbine, condenser, pump, recuperator, pre-heater and generator and power generation is calculated by using these properties. Deviation analysis by comparison calculated and measured power generation and controlling of suitability IPSEpro with ORC module in Scharnhauser Park CHP plant is aimed in this study. In addition, pressure vs. enthalpy graphs of ORC module in Scharnhauser Park is plotted by using Excel sheet based on Visual Basic for observation enthalpy change according to pressure and temperature.

SCHARNHAUSER PARK KOMBİNE ISI VE ENERJİ SANTRALİNDE BULUNAN ORGANİK RANKİNE DÖNGÜSÜNÜN SİMÜLASYONU

ÖZET

Son 50 yılda, dünyanın enerji ihtiyacı hızlı bir şekilde artmıştır ve bu artışın gelecekte de devam etmesi beklenmektedir. Enerji kaynaklarının sınırlı olması ve çevresel problemlerin artması ile biyoenerji, diğer yenilenebilir enerji kaynakları gibi, önemli bir alternatif enerji haline gelmiştir. Pişirme ve ısınma için kullanılan geleneksel biyokütle uygarlığın başlamasından beri enerji kaynağı olarak kullanılmak da ve modern biyoenerji kullanımında günümüzde hızlı bir artış gözlenmektedir. Biyoelektrik verimliliği fosil yakıtlara göre düşük olsa da, biyokütle elektrik üretiminde karlı bir seçenek sunmaktadır. Tarım, orman ve kentsel atık gibi biyo atıklar ve bu atıklardan üretilen biyoyakıtlar birçok biyokütle güç üretim santralinde yakıt olarak kullanılmaktadır. Kombine ısı ve enerji başka bir deyişle kojenerasyon teknolojisi, düşük elektrik verimliliğine sahip üretimlerde; örneğin biyo atıklardan güç eldesi; tercih edilmektedir. Bu teknoloji ile, ısı ve elektriğin eş zamanlı üretilmesinden dolayı, enerji üretimi daha verimli hale gelmektedir. Kombine ısı ve enerji santrallerinde daha çok enerji daha az yakıt ile üretilmek de ve bundan dolayı CO₂ emisyonlarının azalmasını sağlanmaktadır. Orta ve küçük ölçekli kombine ısı ve enerji santrallerinde Organik Rankine Döngüsünün kullanımı biyokütleden enerji üretimi için etkili bir seçenektir. Bu döngülerde, Rankine döngüsünün aksine su yerine organik sıvı kullanılmaktadır. Böylece düşük sıcaklıklı ısı kaynağından daha yüksek verimlilik de güç elde edilebilir. Dünyada enerji kaynağı olarak biyokütleyi kullanan ve Organik Rankine Döngüsü ile enerji üreten birçok kombine ısı ve enerji santrali bulunmaktadır. Stuttgart Almanya'da bulunan Scharnhauser Park bölgesinin enerji sağlama sistemi bu teknolojiye iyi bir örnek teşkil eder. Bu santralde odun ve orman atıkları yakılarak ısı ve elektrik üretilmektedir. Üretilen ısı, bölgesel ısınma sisteminde kullanılmaktadır. Bu çalışmada, Scharnhauser Park kombine ısı ve enerji santralinde bulunan Organik Rankine Döngüsünün simülasyon programı sunulmaktadır ve IPSEpro yazılım programı olarak kullanılmıştır. Scharnhauser Park'da bulunan santralden alınan yirmi sekiz veri grubu kullanılarak güç üretim miktarı IPSEpro ile saptanmıştır. Bu veriler termal yağ, turbin, kondensatör, pompa, ısı geri kazanıcı, ön ısıtıcı ve jeneratör özelliklerini içermektedir. Ölçülmüş ve hesaplanmış güç üretim miktarı karşılaştırılarak sapma analizi ve IPSEpro yazılım programının Scharnhauser Park kombine ısı ve enerji santralinde bulunan Organik Rankine Döngüsüne uygunluğunun kontrolü bu çalışmada amaçlamıştır. Bununla birlikte, entalpinin sıcaklık ve basınç ile değişimini gözlemlemek için Organik Rankine Döngüsünün basınç ve entalpi grafikleri Visual Basic temelli Excel programında çizilmiştir.

1. INTRODUCTION AND PURPOSE

Energy is one of important necessary for cooking and heating since the beginning of human civilization. Energy demand of the world has sharply increased with industrialization. Therefore, the world needs alternative energy supplies to sustain economic growth and development. Figure 1.1 demonstrates world total primary energy supply between 1971 and 2006. According to figure, in these 35 years, energy consumption has increased to about 100% and it reached to 11741Mtoe in 2006 [1].

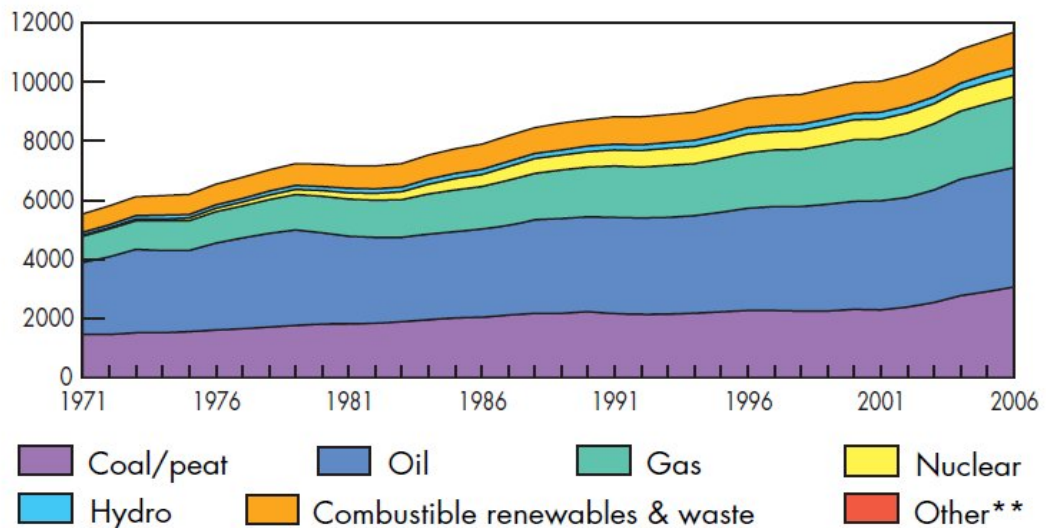


Figure 1.1: Evolution from 1971 to 2006 of world total primary energy supply (Mtoe) [1]

Increase of energy consumption creates some problems such as limitation of energy sources, climate change. Therefore, alternative energy sources have been important very much such as renewable energy. This source provides to reduce carbon emission, clean the air and improve energy security. Therefore, usage of renewable energies has gone up day by day. Global renewable energy capacity grew at rates of 15–30 % annually for many technologies during the five-year period 2002–2006.

According to Global Status Report that was prepared by Renewable Energy Policy Network for the 21st Century (REN21), 18% of the world's final energy consumption came from renewable energy sources in 2006. Distribution of energy consumption in

2006 is showed in Figure 1.2. Renewable energy includes traditional biomass, large hydropower, and new renewables (small hydro, modern biomass, wind, solar, geothermal and biofuels).

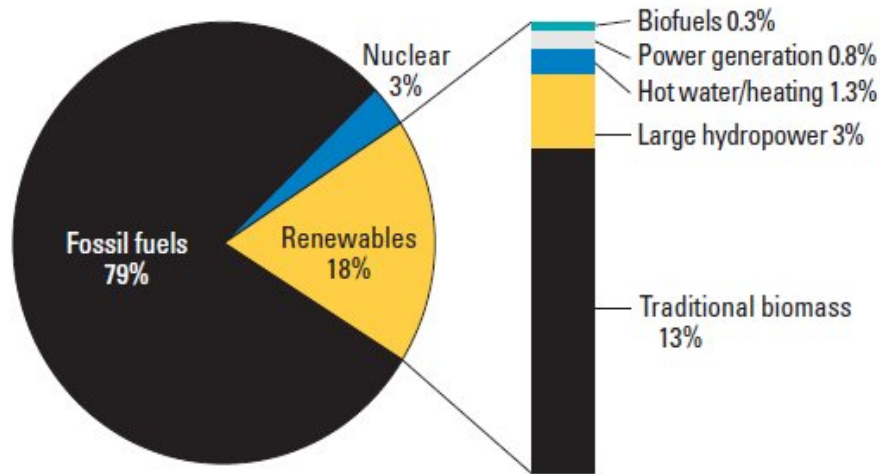


Figure 1.2: Renewable energy share of global final energy consumption, 2006 [2]

Traditional biomass energy for cooking and heating, supplies to about 13% of energy demand of the world. Because of more efficiently modern bioenergy form, usage of traditional biomass has declined. However, even if in developing countries, over 500 million households use traditional biomass for cooking and heating; 25 million households cook and light their homes with biogas [2].

Modern biomass percentage of primary energy change from country to country. In developed countries, this ratio is about 4.1% but all over the world this value decrease to 3.5 %. Utilization of modern biomass ratio is the highest in Brazil as 19.2% [3]. Biofuels also grew rapidly during the period, at a 40% annual average for biodiesel and 15% for ethanol between 2002 and 2006.

One of the major energy demands originates from electricity consumption. Moreover, the electricity sector in many countries is one of the largest contributors to greenhouse gas emissions [4]. Consequently, importance of electricity generation from biomass has increased and its application has become widespread. Power is generally produced from biomass by combined heat and power due to high efficiency. Growing rate of biomass power and heat technology is 3–5% from 2002 to 2006, although in some countries these technologies are growing much more rapidly than the global average [2].

One of good examples of modern biomass technologies application in urban area is Combined Heat and Power Plant (CHP) in Scharnhauser Park and this is biomass fired CHP plant based on an Organic Rankine Cycle (ORC). The most of energy demand of this area is covered to renewable energy. For increase efficiency of renewable energy in Scharnhauser Park, several projects are studied in Hochschule fuer Technik Stuttgart University.

In this study, a simulation program was developed of ORC module in Scharnhauser Park CHP plant and IPSEpro was used as simulation program. Making deviation analysis by comparison calculated and measured power generation and controlling of suitability IPSEpro with ORC module at CHP plant in Scharnhauser Park was aimed.

2. THEORETIC STUDIES

In this section, theoretic studies are represented under the subject headings that are enumerated at below.

- Biomass Theory
- Combined Heat Power Plant (CHP)
- Organic Rankine Cycle
- The Energy Supply System of Scharnhauser Park CHP Plant
- Simulation Programs

2.1 Biomass Theory

Biomass is the living or recently dead biological material that can be used as fuel or for industrial production. Carbon dioxide (CO_2) from the atmosphere and water are absorbed by the plants roots. Then they react in the photosynthetic process to produce carbohydrates whose chemical bonds store solar energy as chemical energy.

Biomass can be acquired directly from plants or indirectly from industrial, domestic, agricultural and animal wastes. The annual world production of biomass is estimated as 146 billion metric tons. Approximately 80% of this amount is attributed to uncontrolled plant growth [5].

Biomass presents alternatives in all fields in industry. Also biomass is important energy source now and importance of this source will be increased in the future. People have used the energy from biomass to burn wood, cook food or keep warm for thousands of years. Utilization of biomass has increased and expanded with development of conversion technologies [6].

Biomass energy, or bioenergy, is energy of biological and renewable origin and the conversion of biomass into useful forms of energy. Biomass is used to meet a variety of energy needs, including generating electricity, heating homes, fueling vehicles and

providing process heat for industrial facilities. This energy is the most prevalent energy among renewable energies.

Biomass can be burned directly or be converted to intermediate solid, liquid or gaseous fuels. A wide variety of conversion routes can be selected that produce a variety of energy carriers in a solid, liquid or gaseous form. These energy carriers address all types of energy markets: heat, electricity and transportation. A number of biomass conversion technologies are currently commercially available. In addition, there is a potential for technological advances and commercialization of more efficient technologies for production of energy. Figure 2.1 shows conversion processes of biomass.

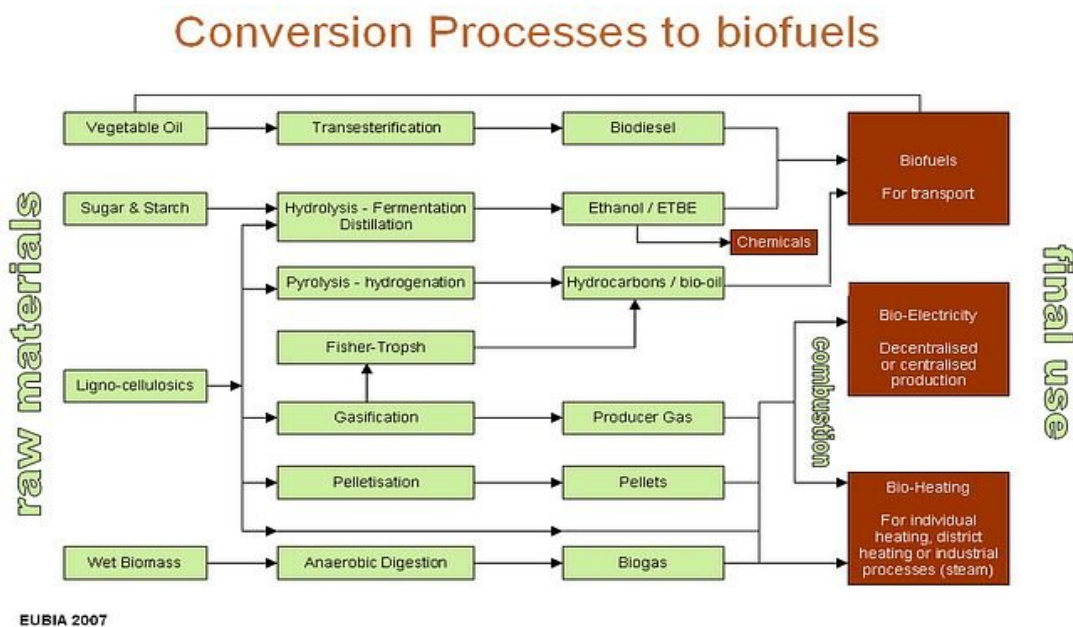


Figure 2.1: Biomass conversion processes [7]

The burning of wood and other solid biomass is the oldest energy technology used. Direct combustion is the most common way of converting biomass to energy, heat and electricity. Worldwide it already provides over 90% of the energy generated from biomass. Compared to the other thermochemical primary conversion technologies (gasification, pyrolysis), it is the simplest and most developed, and biomass combustion systems can easily be integrated with existing infrastructure.

Conversion processes are classified to thermo-chemical conversion processes, bio-chemical processes and physico-chemical.

Thermo-chemical processes convert the original bioenergy feedstock into more operable energy carriers or fuels such as gas, oil or methanol. Compared to the original biomass, these energy carriers have higher energy densities – and lower transport costs – or more predictable and convenient combustion characteristics. These conversion processes are separated to pyrolysis and gasification.

Pyrolysis application is the chemical decomposition of organic materials by heating in the absence of oxygen. Commercial application is either focused on the production of charcoal or production of a liquid product, the bio-oil.

Gasification conversion process is actualized by partial oxidation that is combustion with less oxidizing agent than for complete combustion. The aim of this process is forming carbon monoxide and hydrogen.

Some biomass is too wet to be burnt successfully and so bio-chemical processes are used. This biomass is digested to produce methane rich gas called biogas or fermented to produce alcohols or other specialized chemicals. This conversion process contains anaerobic digestion and fermentation. The former one means microorganism breakdown of organic materials in the absence of oxygen at low temperature to produce biogas principally composed of 60-65% methane, 30-35% carbon dioxide. Fermentation technique is used for converting biomass to ethanol which is probably the most widely used alternative automotive fuel in the world.

Biodiesel that refers to a group of esterified oils with alcohol is produced in physico-chemical processes [7].

Some of conversion technologies are utilized for bioelectricity generation that refers electricity production from biomass or biofuels.

2.1.1 Bioelectricity

Power generation from biomass is a sustainable energy technology which can contribute to substantial reductions in greenhouse gas emissions. Also, bioelectricity has greater potential for environmental, economic and social impacts than most other renewable energy technologies [8].

Bioenergy is one of the profitable options for electricity generation. In 2006, overall electricity generation capacity was 18930 TWh and 3.4% of this generation was supplied by new renewables except large hydropower. Biomass is commonly

employed for both power and heating, with recent increases in biomass use in a number of European countries, particularly Austria, Denmark, Germany, Hungary, the Netherlands, Sweden, and the United Kingdom, and in some developing countries. An estimated 45 GW of biomass power capacity existed in 2006 [1, 2].

Figure 2.2 shows basic stages in a complete integrated biomass to electricity. Biomass can be directly converted to useful energy by combustion process. Released energy from combustion can be converted to electricity. Generating capacities of these plants are constrained by the local availability of feedstock and at low plant sizes steam turbine plant are inefficient generators with high capital costs. Moreover, intermediate liquid or gaseous fuel can be produced by using biomass in conversion process for increased efficiencies and decreased capital costs. These fuels may be used in gas turbines or engines. Applications of electricity generation from biomass, direct combustion, fast pyrolysis, gasification and anaerobic digestion are explained below [9].

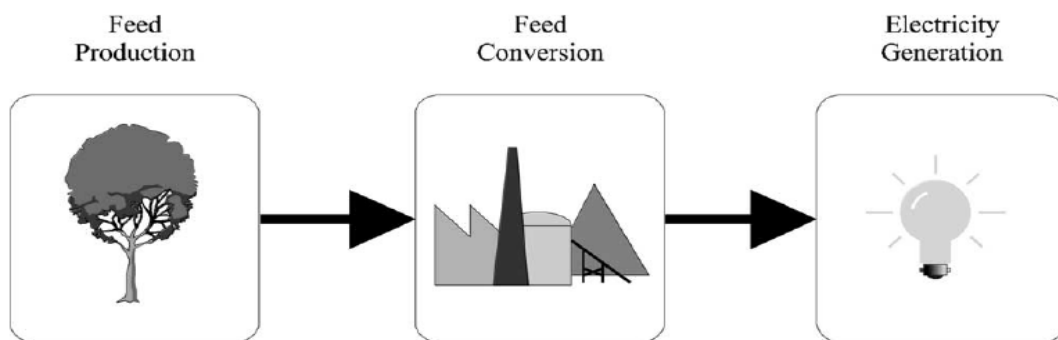


Figure 2.2: Basic stages in a complete integrated biomass to electricity system [9]

In combustion process, chemical bonds in solid biomass are broken. Energy releases as heat and radiation. This energy can be converted to electricity. There are a number of ways of generating electricity using the heat produced in combustion, including the steam turbine, the reciprocating steam engine, Stirling engines, indirect fired gas turbines and direct-fired gas turbines. These equipments will be described under Section 2.2.1 [9, 10].

Pyrolysis is the thermal degradation of biomass in the absence of an oxidizing agent and fast pyrolysis processes are designed and operated to maximize the liquid fraction at up to 75% wt on a dry biomass feed basis. Fast pyrolysis requires rapid heating of the feedstock and rapid quenching of the pyrolysis vapors to minimize secondary reactions. The liquid is a homogenous mixture of organic compounds and

water. Produced liquids can be utilized for heat, chemicals, fuels and electricity applications. Most development for electricity generation is focused on the use of raw pyrolysis liquids in gas turbine or diesel engine applications.

Thermo-chemical gasification is a conversion process by partial oxidation at elevated temperature of a carbonaceous feedstock into a gaseous energy carrier. Ideally, the process produces only a non-condensable gas (CO and H₂) and an ash residue. However, the contaminants such as particulate, tars, alkali metals, fuel-bound nitrogen compounds and some char are formed in gasification process. Produced gas can be used for heat, steam, chemicals and electricity production. Electricity generation could be accomplished in a variety of ways especially gas turbines. Gas turbines are highly sensitive to fuel gas quality, and the fuel gas must be treated to remove contaminants [9].

Anaerobic digestion that is a bio-chemical conversion process means the microorganism breakdown of organic materials in the absence of oxygen at low temperature. This biochemical process produces a gas, called biogas, principally composed of 60-65% methane, 30-35% carbon dioxide and the rest a mixture of other gases. The important advantage of anaerobic digestion when compared to thermochemical processes is that it produces a concentrated nitrogen fertilizer as a by-product. Also this process serves as a means of waste neutralization [7].

Electricity from landfill gas, which is of municipal solid waste (MSW) in landfills, has increased in recent years. Landfill gas contains methane (CH₄) and carbondioxide (CO₂), water vapor, quantities of non-methane organic components and various other trace compounds. In modern landfills, this gas is now usually collected or controlled to prevent its undesirable escape to the atmosphere or its movement through the surrounding soil. Collected gas can be burned in plant for electricity generation after cleaning separation process [10].

Because useful energy and electricity are produced by using combustion of forested waste at plant in Scharnhauser Park, only direct combustion is thorough examined in this study.

2.1.2 Direct combustion of biofuels

Direct combustion is the most common way of converting biomass to energy. It already provides worldwide over 95% of the energy generated from biomass.

Combustion of biomass has been used to burn wood, cook food or keep warm for thousands of years. Up to the early 1900s, much of industrialized society utilized biomass combustion for heating, cooking, chemical and charcoal production, and the generation of steam and mechanical and electric power [12].

Combustion or burning is a complex sequence of exothermic chemical reactions between a fuel and oxygen. In ideal case, carbon dioxide (CO_2) and water are the final products along with energy. Energy releases as radiant and thermal energy, the amount of which is a function of the enthalpy of combustion of the biomass. This energy can be utilized to generation of electricity and heat.

Combustion is classified in complete and incomplete. Complete combustion consists of the rapid chemical reaction of fuel and oxygen. In the idealized case, stoichiometric amounts of fuel and oxygen and in the excess of oxygen are present and react so that each reactant is totally consumed and only carbon dioxide (CO_2) and water are formed. Actually, as combustion reactions come to equilibrium, a wide variety of major and minor species are present. When elements such as carbon, nitrogen, sulfur, and iron are burned, they will yield the most common oxides.

Incomplete combustion occurs when there is not enough oxygen to allow the fuel or combustion air with combustible gases is mixed not well. When carbon incompletely burns in oxygen, carbon monoxide (CO) is produced [13].

The mechanism of solid biomass combustion can be viewed as a stepwise process. All steps occur simultaneously in the combustion chamber. Drying is the first stage of solid combustion and in this step contained moisture in biomass evaporates at low temperature. At about 150 to 200 °C decomposition and devolatilization steps begin on biomass surface. Volatile organic compounds in biomass are released as a gas that burn in the combustion chamber. After that oxygen diffuses to the surface of remaining fuel components in the carbonaceous residue which are combusted at temperatures of about 400 to 800 °C and greater.

Flame temperature can be reached to different level according to process conditions and fuel properties that influence the combustion characteristics. Temperatures can be reached as 1500 °C, when biofuel has no moisture or low moisture and also the combustion process is carefully controlled [12].

In combustion process, chemical bonds in biomass are broken and chemical energy is converted to heat and radiation energy. Biomass has presented important advantages as a combustion fuel because this fuel has the high volatile matter and the high reactivity. However, biomass contains much less carbon and more oxygen than solid fossil fuels. Therefore, it has less heating value [10].

Particle dimensions, bulk and energy density, gross and net calorific value (GCV and NCV) and moisture content are important parameters of biomass. GVC and NCV values are function of chemical composition. These values are proportion to carbon, hydrogen and sulphur contents of fuel. Nevertheless, these values is inverse proportion to nitrogen, oxygen and ash contents.

Carbon, Hydrogen and Oxygen are the main component of biomass fuel. C and H react with O by exothermic reaction during combustion. O in fuel contributes to necessary of oxygen for combustion. Additionally, biomass contains other components such as nitrogen, sulphur, chlorine, sodium, heavy metals etc. Important physical and chemical properties of biomass fuel and their effects are shown in Table 2.1

Physical characteristics and chemical composition of biomass fuel affect the whole process of combustion systems. Fuel quality depends on pre-treatment process. And also it can be improved by suitable these technologies, but this increases costs [3].

Table 2.1: Characteristics of solid biomass fuels and their most important effects [3]

Characteristics	Effects
Physical properties	
Moisture content	Storage durability and dry-matter losses, NCV, self-ignition, plant design
NCV, GCV	Fuel utilization, plant design
Volatiles	Thermal decomposition behaviour
Ash content	Dust emissions, ash manipulation, ash utilization/disposal, combustion technology
Ash-melting behavior	Operational safety, combustion technology, process control system, hard deposit formation
Fungi	Health risks
Bulk density	Fuel logistics (storage, transport, handling)
Particle density	Thermal conductance, thermal decomposition
Physical dimension, form, size distribution	Hoisting and conveying, combustion technology, bridging, operational safety, drying, dust formation
Fine parts (wood pressings)	Storage volume, transport losses, dust formation
Abrasion resistance (wood pressings)	Quality changes, segregation, fine parts

Table 2.1: Characteristics of solid biomass fuels and their most important effects (Continues) [3]

Chemical properties, Elements	
Carbon, C	GCV
Hydrogen, H	GCV, NCV
Oxygen, O	GCV
Chlorine, Cl	HCl, PCDD/PCDF emissions, corrosion, lowering ash-melting temperature
Nitrogen, N	NO _x , N ₂ O emissions
Sulphur, S	SO _x emissions, corrosion
Fluorine, F	HF emissions, corrosion
Potassium, K	Corrosion (heat exchangers, superheaters), lowering ash-melting temperature, aerosol formation, ash utilization, fouling
Sodium, Na	Corrosion, lowering ash-melting temperature, aerosol formation
Magnesium, Mg	Increase of ash-melting temperature, ash utilization
Calcium, Ca	Increase of ash-melting temperature, ash utilization
Phosphorus, P	Ash utilization
Heavy metals	Emissions, ash utilization, aerosol formation

2.1.3 Direct combustion systems

Selection and design of combustion equipment is very important to improve efficiencies, reduce cost and maintain environmental and process safety. Process control systems with fully automatic system equip in advanced combustion plant. Therefore, the necessary of manual fuel feeding can be eliminated and labor cost can be decrease. Moreover, emission level can decrease.

Advanced combustion system can be classified to fixed bed combustion, fluidized bed combustion, dust combustion. The basic principles of these three technologies are shown in Figure 2.3.

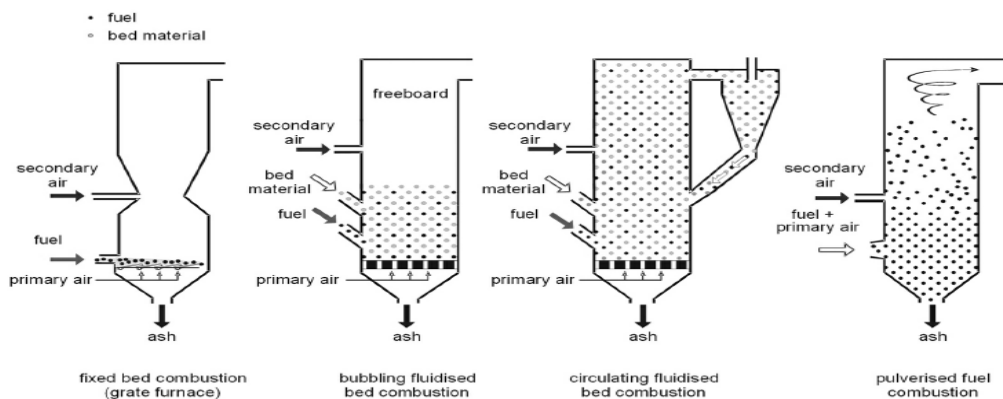


Figure 2.3: Principal combustion technologies for biomass [3]

2.1.3.1 Fixed bed combustion

In this system, combustion zone is distinguished from the fuel bed. Primary air enters to a fixed bed and in this zone drying, gasification and char combustion consist. Combustible gases that produce in primary zone pass through second zone where these gases are burned with secondary air. Fixed bed combustion systems contain grate furnaces and underfeed stokers.

Grate furnaces are suitable for biomass fuels that have high moisture content, varying particle sizes and high ash content. Using mixtures of wood fuels and straw, cereals and grass that have their different combustion behavior, low moisture content and low ash-melting point does not permit for this technology. There are different grate furnace technologies available: fixed grates, moving grates, traveling grates, rotating grates and vibrating grates and these furnaces can operate as counter-current flow, co-current flow and cross-flow. These technologies should be selected and planned carefully according to fuel properties. Since, all of these technologies have specific advantages and disadvantages.

Underfeed stokers represent a cheap and operationally safe technology for small- and medium-scale systems up to a nominal boiler capacity of 6 MWth. These combustors are appropriate for biomass fuels with low ash content and small particle sizes (particle dimension up to 50 mm). Combustion of ash-rich biomass fuels in this technology needs ash removal system.

2.1.3.2 Fluidized bed combustion

Fluidized bed combustion (FBC) systems have performed for combustion municipal and industrial wastes since 1960. A fluidized bed is equipped with a perforated bottom plate in a cylindrical vessel filled with a suspension bed of hot, inert and granular material (silica sand and dolomite etc.). Biomass fuel is combusted in a self-mixing suspension of gas and this solid-bed material. 90–98 per cent of the mixture of fuel and bed material exists in the bed.

Fluidization in bed is supplied by primary air that enters below of the bed and passes through the air distribution plate. Consequently, particles start to seethe and bubbles occur. The intense heat transfer and mixing provides good conditions for a complete combustion with low excess air. Also, due to the good mixing achieved, various fuel mixtures can be used in fluidized bed combustion plants (e.g. mixtures of wood and

straw can be burned). However, these combustion plants are limited by fuel particle size and impurities contained in the fuel. Therefore, appropriate fuel pre-treatment systems are needed such as particle size reduction and separation of metals. According to the fluidization velocity, FBC can be classified to bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) combustion.

BFB furnaces are operated in plants have capacity of over 20 MWth. The particle size of fuel should be lower than 80 mm. And also the fluidization velocity of the air varies between 1.0 and 2.5 m/s. The advantage of BFB furnaces is their flexibility concerning particle size and moisture content of the biomass fuels. Nevertheless, BFB furnaces have one big disadvantage that the difficulties they have at partial load operation. This problem deals with splitting or staging the bed in modern furnaces.

In CFB furnaces, the velocity of air is between 5-10 m/s and fuel particle size below 40 mm is recommended for these furnaces. A better heat transfer and a very homogeneous temperature distribution are achieved by the higher turbulence in the bed. Advantage of these furnaces is the control of air staging and the placement of heating surfaces right in the upper part of the furnace. It is important for stable combustion conditions. One disadvantage of CFB is that more sand particles leave with flue gas than BFB. Also, necessity of small fuel particle, which often causes higher investments in fuel pre-treatment, larger size of these furnaces are other disadvantages of CFB.

2.1.3.3 Dust combustion

Dust combustion systems are appropriate for combustion of fuels having small particle size. Fuel quality has to be quite constant and the fuel should have maximum moisture content as 20%. In addition, fuel particle size should not be more than 10-20 mm. Due to the small particle size, gasification and charcoal combustion of biomass consist at the same time. Therefore, quick load changes and an efficient load control can be achieved.

Fuels are injected into the furnace with primary air that is used as transportation air. Secondary air is added in order to achieve a good mixture with the combustible gases. Appropriate air staging provides low excess air amounts and low NO_x emissions. The most important disadvantage of dust combustion is thermal stress and erosion. For this reason, insulation bricks wear out quickly. Another disadvantage is

an extra start – burner is necessary such as fuel oil or natural gas. Muffle furnaces and cyclone burners are mostly employed as dust combustion system [3].

2.1.4 Energy balance of direct combustion

Chemically energy in chemical bond of biomass is converted heat and radiation energy by combustion of biomass. For determination of combustion temperature and efficiency, energy calculation is needed. A general energy balance equation is shown below.

Stored energy in biomass is shown as energy in fuel in Equation 2.1 and the preheat energy is an energy difference because of temperature differences between the fuel or air and ambient conditions. And also the energy stored in flue gas at specific temperature is called as the energy in flue gas. Lost of energy by incomplete combustion and heat loss to surroundings is pointed to energy losses.

$$\text{Energy in fuel} + \text{Preheat energy} = \text{Energy in flue gas} + \text{Energy losses} \quad (2.1)$$

The energy in the fuel can be determined by multiplying the net calorific value (NCV) and fuel mass flow ($\dot{m}_F$). NCV is described as the released heat in the time of combustion per mass unit of fuel under the limitation that the water phase is gaseous form in the same period and that the water and the flue gas have the same temperature as the fuel prior to combustion.

The NCV is calculated by Equation 2.2 where h is concentration of hydrogen in weight percent (dry basis, d.b.), w is moisture content of fuel in weight percent (wet basis, w.b.). Δh is enthalpy difference between gaseous and liquid water and this value is determined as 2.444 MJ/kg. M_i is molecular mass of i component. NCV also depends on gross calorific value (GVC). This value which is estimated by Equation 2.3 is function of the content of components of fuel in weight percent, X_i (d.b) and their calorific value (coefficient of X_i). Definition of GVC is same of NCV apart from GVC is determined under constraint that the water form during combustion is in liquid phase.

$$NCV = GVC \left(1 - \frac{w}{100} \right) - \Delta h \frac{w}{100} - \Delta h \frac{h}{100} \frac{M_{H_2O}}{M_{H_2}} \left(1 - \frac{w}{100} \right) [Mj / kg, w.b.] \quad (2.2)$$

$$GVC = 0.3491X_C + 0.1005X_S - 0.0151X_N - 0.1034X_O - 0.0211X_{ash} [MJ / kg, d.b] \quad (2.3)$$

The pre heat energy and the energy in fuel are calculated by estimation of enthalpy difference at ambient and final temperature. Enthalpy of component is calculated by using Equation 2.4. The coefficients of each species can be found in Ref. 3. Determination of overall enthalpy of air, fuel and flue gas is shown as Equation 2.5.

$$h_i(T) = T \left(a_1 + \frac{a_2}{2}T + \frac{a_3}{3}T^2 + \frac{a_4}{4}T^3 + \frac{a_5}{5}T^4 + \frac{a_6}{T} \right) \frac{R_u}{M_i} \left[\frac{J}{kg \cdot i} \right] \quad (2.4)$$

$$h = \sum X_i h_i \quad (2.5)$$

Energy losses due to incomplete combustion and unburned carbon are estimated by Equation 2.6 where CV_i and $\bar{m}_i$ are calorific value of species and mass of species per kilogram of wet ash-free fuel (waf). Sum of the heat losses by radiation, convection and conduction is pointed as $\sum Q_i$.

$$\bar{E}_i = CV_i \bar{m}_i \left[\frac{kJ}{kg \text{ fuel (waf)}} \right] \quad (2.6)$$

Finally, the general energy balance equation (Equation 2.1) becomes:

$$NCV\dot{m}_F + [h_F(T_F) - h_F(T_{Amb})]\dot{m}_F + [h_{Air}(T_{Air}) - h_{Air}(T_{Amb})]\dot{m}_{Air} = [h_{FG}(T_{FG}) - h_{FG}(T_{Amb})]\dot{m}_{FG} + \sum_i Q_i + \sum_j \bar{E}_j \dot{m}_F \quad (2.7)$$

If there are no any energy losses and no preheating, the general energy balance can be simplified to Equation 2.8 [3].

$$NCV\dot{m}_F = [h_{FG}(T_{FG}) - h_{FG}(T_{Amb})]\dot{m}_{FG} \quad (2.8)$$

2.1.5 Environmental aspects of biomass combustion

The most important advantage of bioenergy is positive environmental benefit of biofuels especially in point of the global balance of green house gas (GHG) emissions. All processes contain bioenergy systems on a full fuel-cycle basis with the

aim of establishing overall GHG balances are investigated by IEA (International Energy Agent) Bioenergy Task 38 (Greenhouse Gas Balances of Biomass and Bioenergy Systems). This is not a worthless case, because biomass usage for energy is not completely GHG neutral. [3].

The earth's atmosphere presently contains some 380 ppm of carbon dioxide. Nearly ten billions tons of CO₂ is produced each year by the combustion equipment to raise the CO₂ content of atmosphere at a rate of 1 ppm [13]. Although today the air pollution from biomass combustion applications are far from negligible, emission of biomass combustion is lower than fossil fuel. Emissions being based on biomass combustion applications can be classified in emission from complete and incomplete combustion.

With complete combustion, the formation of toxic, noxious and corrosive products can be minimized or eliminated even so CO₂, NO_x, SO_x, HCl, particles and heavy metals emissions can actualize. A major combustion product based on biomass combustion is CO₂ like other carbon content fuel combustion. Nevertheless, biomass is a renewable fuel, and is considered as being CO₂-neutral with respect to the greenhouse gas balance.

As a result of complete combustion of fuel that contains nitrogen, nitrogen oxides (NO_x) emissions occur. This component consists by both the gas phase and char combustion. Also, NO_x emissions increase with excess air ratio and combustion temperature. Since N₂ and O₂ partly combine to form NO_x at high temperature as 1500 to 2000°C. If these oxides are slowly cooled, they decompose to N₂ and O₂. The main components of nitrogen oxides from biomass combustion are NO, NO_x, N₂O.

The sulfur oxides (SO_x) are poisonous. These component emissions which are result of complete oxidation of sulphur fuel include most SO₂ and some SO₃ formed at low temperature. All sulphur (S) in fuel can not be converted to SO_x. A trivial amount of salt (KSO₄) and H₂S remain in the ashes.

If biomass containing higher amounts of chlorine (Cl) as fuels, HCl release from biomass combustion application. Washing of fuel provide reduction of HCl emission. The major fraction of Cl reacts with K and Na and KCl and NaCl are produced. Aerosols are from these components and also K₂SO₄. Aerosols and coarse fly-ash

create fly ash that causes particle emission. Moreover, virgin biomass includes heavy metal (Cu, Pb, Cd, and Hg) that remain in the ash or evaporate and attach to surface of fly ash.

Reasons of incomplete combustion are insufficient mixing of combustion air and fuel, lack of available oxygen, too low combustion temperature and too low short residence times. Some components, such as CO, CH₄, some hydrocarbons, particles etc., are emitted to atmosphere via incomplete combustion in biomass combustion applications.

Carbon monoxide is the main product of incomplete combustion. When oxygen and residence time is sufficient, it converts to CO₂. Also this product is poisonous and undesirable for biomass combustion. An important intermediate in the conversion of fuel carbon to CO₂ and fuel hydrogen to H₂O is methane (CH₄) that is a direct greenhouse gas. Apart from CH₄, some hydrocarbons emissions are observed due to incomplete combustion in biomass application. Most important of these emissions is PAH emission that has carcinogenic effects. Particle emissions include soot, char or condensed heavy hydrocarbons (tar) at low combustion temperature, too short residence time and lack of available oxygen. Ammonia (NH₃), ozone, polychlorinated dioxins and furans are other emissions of incomplete combustion. Pollutants of biomass combustion and their effects are tabulated in Table A.1 (Appendix A1) [3, 13].

2.2 Cogeneration Plant

Power plants with gas turbine are typically only 30-40% efficient in converting the energy of the fuel into electricity. The rest of the energy is lost as waste heat [14]. Efficiency of energy can be increased by combined heat and power plant (CHP) which can produce heat and power simultaneously [15].

The production of electricity and heat in one single process is defined as cogeneration or Combined Heat and Power. By usage of cogeneration, waste heat of electrical generation is minimized. In conventional electricity generation, more than 55% of fuel energy is not converted into useful energy even if the most advanced technologies are being used. Figure 2.4 show energy losses in conventional plant [16].

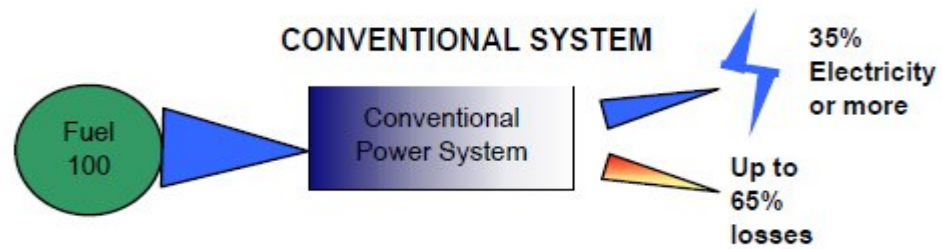


Figure 2.4: Energy losses in conventional electricity generation [16]

The cogeneration plant efficiency can reach 90% or more by the utilization of waste heat. Also, in conventional electrical plant, 5-10% of electricity is lost through the transmission and distribution of electricity. However, the electricity generated by the cogeneration plant is normally used locally, and then transmission and distribution losses are negligible.

Energy savings in cogeneration plant is between 15-40% when compared to the supply of electricity and heat from conventional power stations and boilers [17]. Energy loss is determined as about 10% and energy loss of CHP is shown in Figure 2.5.

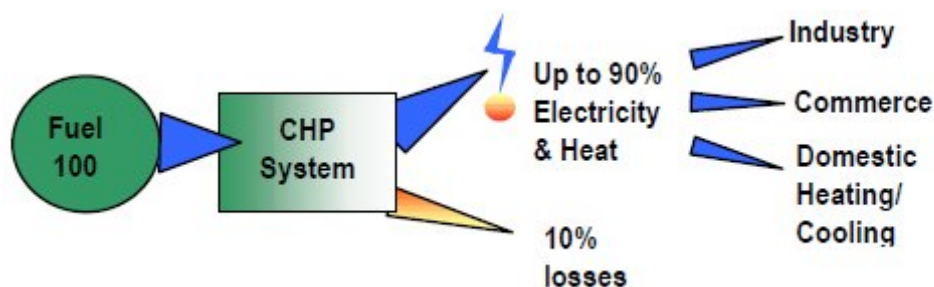


Figure 2.5: Energy losses in CHP plant [16]

In cogeneration process, residual heat can be transferred to various mediums such as warm water, steam or hot air. These mediums can be used for commercial and industrial. Moreover, it is possible to do trigeneration that is used for generation of electricity, heat and cooling simultaneously. Cooling is produced through an absorption or adsorption chiller [16].

Beside high efficiency of energy, CHP has various benefits. These benefits are arranged below.

- CO₂ emissions are lower to the environment because more energy can be produced by using less fuel.

- Biomass fuels and some waste materials such as refinery gases, process or agricultural waste can be used as fuel in cogeneration plant so operational cost and the need for waste disposal are decreased.
- Large cost savings, heat can be affordable by domestic users
- Decentralized electricity generation grows up if plant is designed to meet the needs of local consumers thus providing high efficiency, avoiding transmission losses and increasing flexibility in system use
- Cogeneration improves local and general security of supply - local generation. The risk that consumers are left without supplies of electricity and/or heating can be decreased.
- Cogeneration provides reduces the import dependency - a key challenge for energy future because the fuel need is reduced through cogeneration
- The diversity of generation plant and competition in generation increase.
- Employment increase. A number of studies have now concluded that the development of cogeneration systems is a generator of jobs [17].

2.2.1 Cogeneration technologies

Generally, cogeneration technology can implement in all electricity generation process using thermal combustion. It is a general principle applicable to various technologies. Cogeneration principle demonstrates Figure 2.6. Cogeneration schemes can be optimized to supply their specific needs by thoroughly analyzes [18].

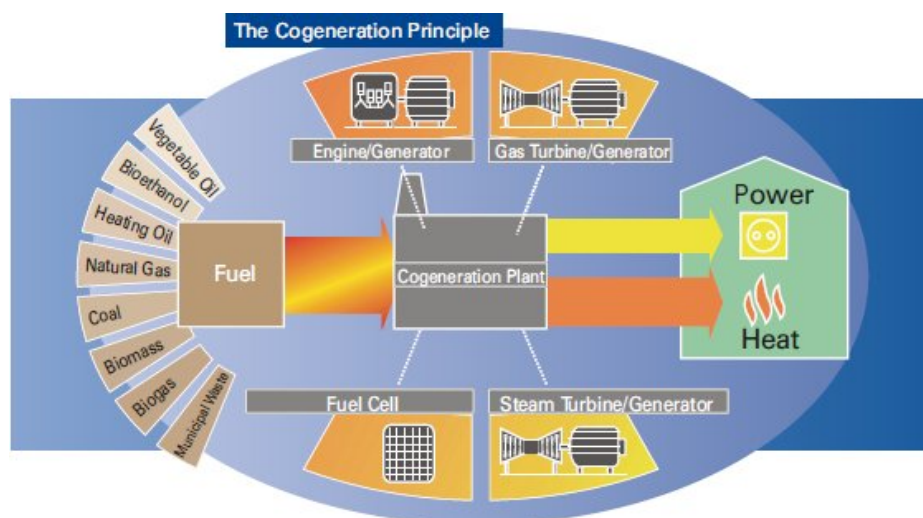


Figure 2.6: Cogeneration principle [18]

Heat/power ratio changes from site to site. Therefore, the type of plant must be selected carefully and an appropriate operating regime must be established to match demands as closely as possible. The plant may be set up to supply a part or all of the site heat and electricity loads, or an excess of either may be exported if a suitable customer is available [17].

Cogeneration plant can be classified to Topping Cycle plants and Bottoming Cycle plants. Major aim of topping cycle is electricity generation and residual energy is utilized to produce useful energy. Simplified cogeneration topping cycles is shown in Figure 2.7.

Topping cycle options include;

- Extracting Steam Turbines
- Back-Pressure Steam Turbines
- Gas Turbines
- Gas Turbine With Waste Heat Boiler
- Combined Cycles (Steam Turbine and Gas Turbine)
- Diesel and Gas Engines
- Fuel Cells

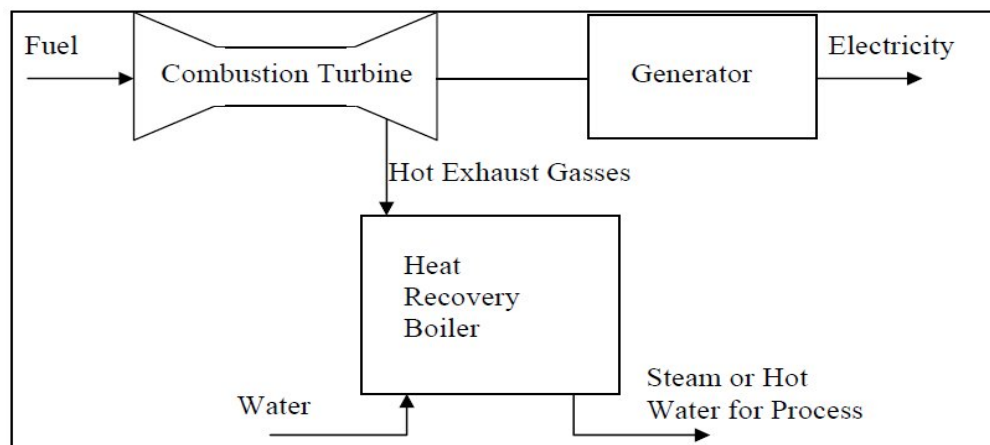


Figure 2.7: Simplified cogeneration topping cycle [15]

In the bottom cycle process that is demonstrated in Figure 2.8 the heat energy is employed in an industrial process. After that the relatively low-on-energy stream is used for electricity generation. This type plants are only used when the industrial

process requires very high temperatures, such as furnaces for glass and metal manufacturing, so they are less common. Bottoming cycle options include Low Pressure Rankine Cycles, Stirling Cycles and Brayton Cycles [15]

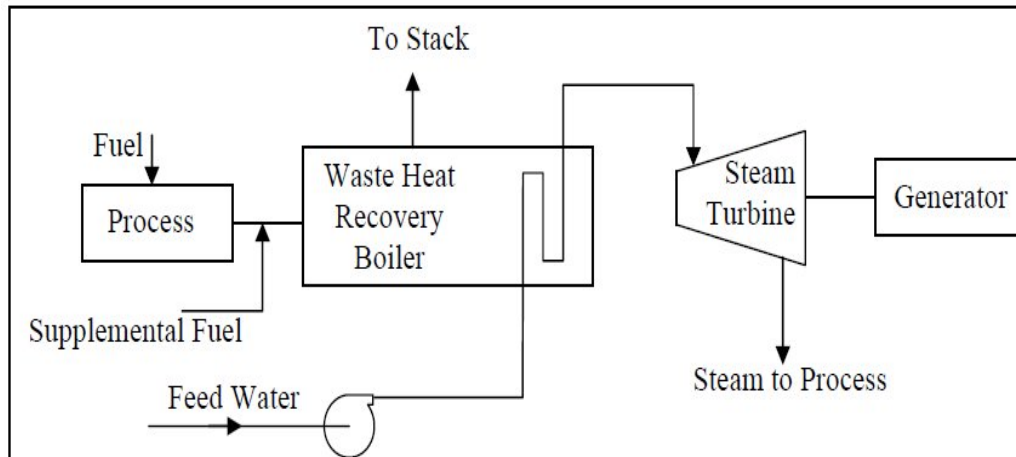


Figure 2.8: Simplified cogeneration bottoming cycle [15]

A cogeneration plant consists of four basic elements. These are a prime mover (engine), an electricity generator, a heat recovery system, a control system. The prime mover converts thermal energy to mechanical energy. The prime mover drives the electricity generator and waste heat is recovered. The basic elements are all well established items of equipment, of proven performance and reliability.

Depending on the site requirements, the prime mover may be a steam turbine, reciprocating engine, gas turbine or combined cycle. And also, new developments are bringing new technologies towards the market and it is expected that some of these technology become economically available in next ten years. The new technologies are fuel cells, stirling engine and micro turbine.

- Steam Turbines have been used as prime movers for industrial cogeneration systems for many years. High-pressure steam raised in a conventional boiler is expanded within the turbine to produce mechanical energy, which may then be used to drive an electric generator. This system generates less electrical energy per unit of fuel than a gas turbine or reciprocating engine-driven cogeneration system, although its overall efficiency may be higher, achieving up to 84%
- The gas turbine has become the most widely used prime mover for large-scale cogeneration in recent years, typically generating 1-100 MWe. On gas turbine based system has lower capital cost. The fuel is burnt in a pressurized combustion chamber

that is integral with the gas turbine. The hot pressurized gases are used to produce mechanical energy. Residual energy of hot exhaust gases can be used to produce wholly or partly the thermal energy.

- The reciprocating engines used in cogeneration are internal combustion engines operating on the same familiar principles as their petrol and diesel engine automotive counterparts. This system is similar to gas turbine system. But the main difference is that reciprocating engines give a higher electrical efficiency, but it is more difficult to use the thermal energy they produce.
- Some large systems that have generally power output greater than 3 MWe utilize a combination of gas turbine and steam turbine. The hot exhaust gases from the gas turbine are used for production of the steam for the steam turbine. This is called a combined cycle.
- Stirling engines are indirectly fired gas engines are used in a closed cycle. Heat is supplied to this engine by an external source, such as burning gas this is working medium. The efficiency of these machines is potentially greater than that of internal combustion or gas turbine devices.
- Manufacturers are developing smaller and smaller systems and nowadays there are microturbines as small as 25 kWe. In general, microturbines can generate from 25 kWe to 200 kWe of electricity.
- Fuel cells convert the chemical energy of hydrogen and oxygen directly into electricity without combustion and mechanical work such as in turbines or engines. A typical single cell delivers up to 1 volt. In order to get sufficient power; fuel cells are connected to each other.

Generators convert the mechanical energy into electricity. They can be either synchronous or asynchronous. The former one can operate in isolation from other generating plant and the grid. An asynchronous generator can only operate in parallel with other generators, usually the grid. Synchronous generators are usually more expensive than asynchronous units at system has outputs below 200 kWe.

The heat recovery boiler is an essential component of the cogeneration installation. It recovers the heat from the exhaust gases of gas turbines or reciprocating engines. The simplest one is a heat exchanger through which the exhaust gases pass and the

heat is transferred to the boiler feed water to raise steam. The cooled gases then pass on the exhaust pipe or chimney and are discharged into the atmosphere [17]. Electricity generation from heat of exhaust gas can be more complicated.

2.2.2 Applications of cogeneration

A wide variety of fuels can be utilized for cogeneration. Solid, liquid or gaseous fossil fuels currently precedence as fuel for CHP. Moreover, cogeneration from biomass fuels is becoming increasingly important. Sometimes, waste, refinery gases, landfill gas, agricultural waste or forest residues can be used as fuels. These substances increase the cost-efficiency of cogeneration [16].

Cogeneration schemes can have different sizes to provide outputs from 1 kWe to 500 MWe. For larger scale applications that are greater than 1 MWe, no standard cogeneration kit exists: equipment is specified to minimize cost. However, in small – scale cogeneration, equipment is normally available in prepackaged units for simplify installations.

In recent years cogeneration has become an attractive and practical proposition for a wide range of applications.

- Industrial cogeneration schemes are generally taken place on some industries that has high electricity and heat demand. Suitable examples are found in the refining, paper, chemicals, oil, greenhouses and textile sectors. Capacity of industrial cogeneration is over 1 MWe. The requirements for heat in industry are often in the form of steam and hence the majority of modern industrial cogeneration systems are based on gas turbines. A number of larger schemes use combined cycle cogeneration.
- District heating cogeneration is utilized to provide space heating and hot water for domestic, commercial or industrial use. This cogeneration application is commonly available in urban areas in northern, central and eastern Europe. Municipal waste and biomass can be used for fuel of district heating cogeneration and also the use of natural gas as a fuel gives added flexibility to district heating systems.
- Residential and commercial cogeneration applications are smaller systems and generally on the basis of packaged units. Packaged units comprise a reciprocating engine, a small generator, and a heat recovery system, housed in an acoustic container. These systems are commonly used in hotels, leisure centers, offices,

smaller hospitals, and multi-residential accommodation. Larger applications are based on technology that is similar to the cogeneration systems used in industry, gas turbines, or larger reciprocating engines. Such systems are used in larger hospitals, large office complexes, universities and colleges.

- Trigeneration can be defined as the conversion of a single fuel source into three energy types that are electricity, heating and cooling. This application provides production of electricity, steam or hot water and chilled water with lower pollution and greater efficiency. Trigeneration can be applied to all the applications of cogeneration: District cooling, cooling demand in industries and cooling in individual buildings [17].

2.2.3 Power generation from biomass

Biomass uses for power and CHP plants have generally smaller size and lower electrical efficiency than coal plants [23]. However, usage of biomass and municipal solid waste (MSW) provides lower of operation cost of plant and need for waste disposal [17]. Electrical efficiencies of these plants are 30%-34% and 22% for dry biomass and solid waste respectively. In cogeneration mode, the total efficiency may reach 85%-90%.

Biomass power and CHP generation regularly increases in Europe countries especially in Austria, Germany, the United Kingdom, Denmark, Finland and Sweden. Bioelectricity is mostly produced from wood residues and MSW in cogeneration plants in these countries. Rising amount of global biomass power capacity was 2–3 GW in 2005 according to REN21 Global Status Report 2006 and total capacity increased to 44 GW in this year. In 2004, registered annual capacity increased from 50% to 100% or more in Germany, Hungary, the Netherlands, Poland, and Spain. Australia, Austria, Belgium, Denmark, Italy, South Korea, New Zealand and Sweden raise this capacity in the range of 10%–30%. In the United States 85% of total wood process wastes are used for power generation excluding forest residues.

China, Brazil, Latin American, Thailand, Cambodia and India are turning increasingly to biomass power plants. Some 70 MW of small-scale biomass gasification systems for off-grid power generation and 3.8 million household-scale biogas plants are installed in India. China reported 17 million existing biogas users in

2005. Use of biomass stoves is growing in Africa (Morocco, Uganda, Malawi, and Ethiopia). Heat and power generation from biomass accounted for 7% of some \$38 billion invested in new renewable energy capacity worldwide in 2005 (excluding large hydro).

Biomass combustion systems can be used for power generation especially cogeneration applications. Due to the scarce availability of local feedstock and the high transportation cost, the typical size of these plants is ten times smaller (from 1 to 100 MW) compared to coal-fired plants. Nevertheless, a few large-scale plants are available.

This technology is used to dispose of large amounts of residues and wastes (e.g. bagasse). Electrical efficiency can reach 33%-34% by using high-quality wood chips in modern CHP plants with maximum steam temperature of 540°C. Also, efficiency can be improved to 40% if operated in electricity-only mode. Net carbon emissions per unit of electricity are below 10% of the emissions from fossil fuel-based electricity.

New CHP plant designs using MSW are expected to reach 28%-30% electrical efficiency, and above 85%-90% overall efficiency in CHP mode if good matching is achieved between heat production and demand. Moreover, electricity production from MSW offers a net emission saving between 725 and 1520 kg CO₂/t MSW. Saving is even higher for CHP [23].

2.3 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is similar to the cycle of a conventional Rankine except for the fluid that drives the turbine. Instead of water, a high molecular mass organic that has lower boiling temperature is used as working medium. This enables exploiting efficiently low temperature heat sources (70-300°C) to produce electricity in a wide range of power outputs [3].

2.3.1 Operation of ORC

The simple Rankine cycle that is a steam power cycle has the same component layout as Carnot cycle. Figure 2.9 demonstrates flow chart of simple Rankine cycle.

The working fluid is pumped to a boiler where it is evaporated, passes through a turbine and is finally re condensed.

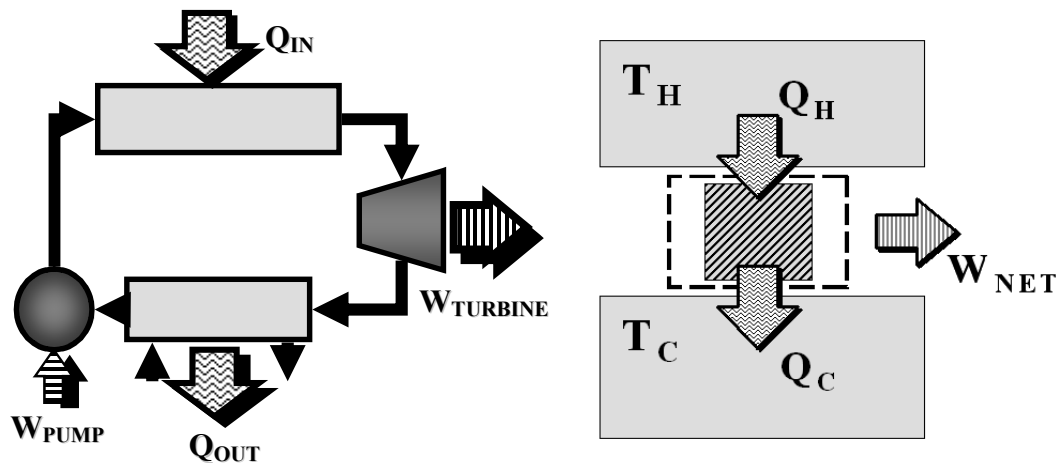


Figure 2.9: Simple Rankine cycle [20]

The simple Rankine Cycle continues the condensation process until the saturated liquid line is reached. The T-s diagram can give an idea of the cycle efficiency. The more rectangular the cycle, the closer to the ideal Carnot cycle, has the higher the efficiency. The T-s diagrams of ideal Organic Rankine and Rankine cycle are shown in Figure 2.10, left one is diagram of silicon oil (MDM) and another is water T-s diagram. According to water T-s diagram, in ideal Rankine cycle process, pressure of water in pump increases at isentropic process (1-2). Heat is given to working medium in boiler at constant pressure or isobaric process (2-3). In turbine, isentropic expansion occurs (3-4). Finally, heat of working medium is transferred at constant pressure in condenser (4-1) [19, 20]

In reality, the effect of the irreversibilities in the cycle is a reduction of cycle efficiency and of useful work output. The main irreversibilities are losses in the pump and in the expander (friction, leakage, etc.); pressure drops in the heat exchangers and inefficiencies in the heat exchangers.

The usual working fluid for Rankine cycles is water under pressure. In the case of a low temperature process, the boiling temperature of working medium has to be much lower. The water/steam working fluid is not appropriate for this process because of its low efficiency under these conditions. Water also shows a high vaporization specific volume that imposes larger installations. Therefore, refrigerants or hydrocarbons as working fluid which has lower boiling temperature is used as working medium. This cycle is called Organic Rankine Cycle (ORC).

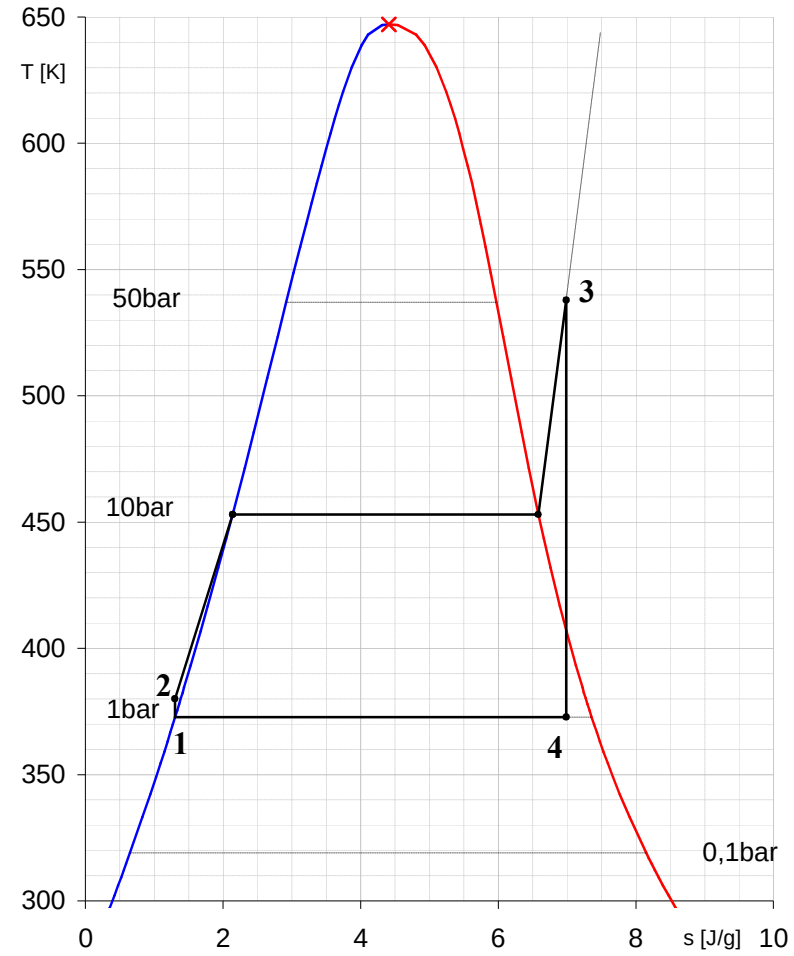
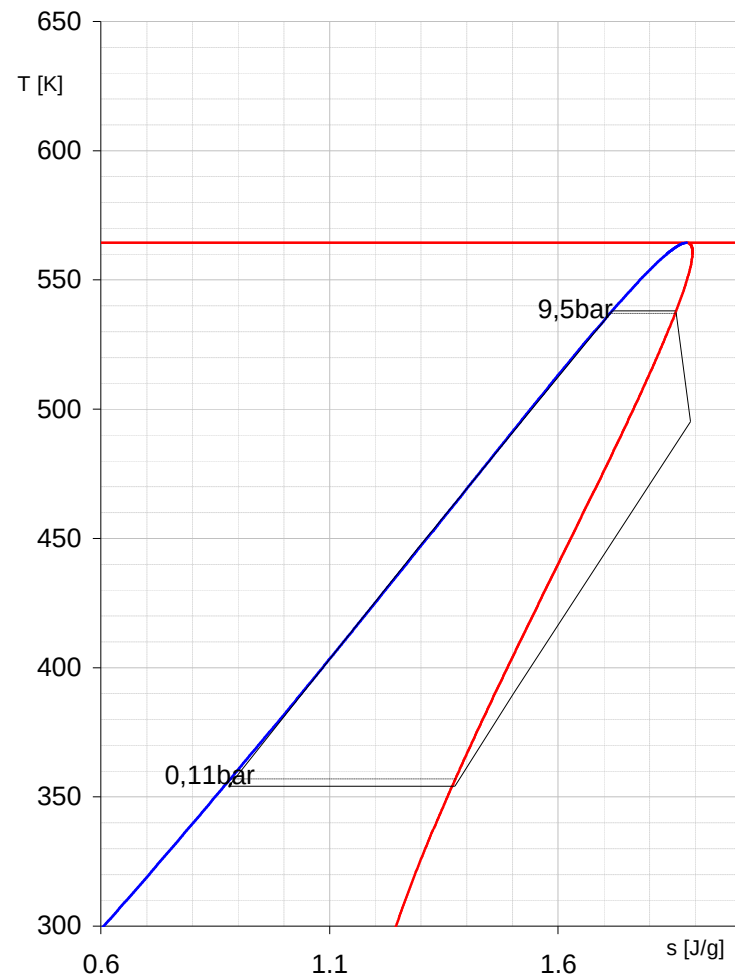


Figure 2.10: The T-s diagram of ideal Rankine and Organic Rankine cycle [21]

The ORC efficiency can be improved by the addition of a regenerator or recuperator. The use of a recuperator is justified when the slope of the saturation vapor curve is positive such as isopentane, silicone oil. More generally when the fluid is still strongly overheated after the expansion, these equipments can be used. It is situated at the exhaust of the pump on the high pressure side, and between the expander and the condenser on the low pressure side [19].

As represented in Figure 2.11, the ORC essentially consists of five components: Evaporator (6-1), turbine (1-2), recuperator (2-3/5-6), condenser (3-4) and feed pump (4-5). Moreover, the temperature entropy diagram in figure shows change of situation of working medium.

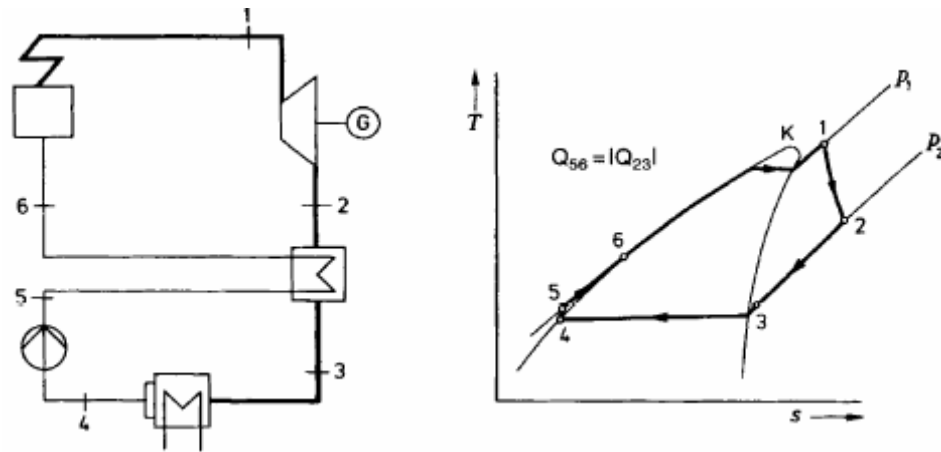


Figure 2.11: Flowchart and the T-s diagram of the ORC process with recuperator [21]

The following process steps take place:

4-5: Before the pump, the stream has the lowest pressure and the lowest temperature of the working medium occurs in this process. Pressure is raised by feed pump the highest pressure level and thereby increases easily in temperature.

5-6: On the liquid side of the recuperator warmth is supplied to the fluid by the gas side.

6-1: The liquid working medium is sent to the evaporator where heat is transfer to the working medium in order to be the saturated or superheated steam.

1-2: Evaporated medium is expanded in turbine. It is connected to generator that converts mechanical energy to electricity. Therefore, mechanical losses can be minimized.

2-3: The expanded gas organic medium is cooled in a recuperator to increase the ORC cycle efficiency.

3-4: Residual heat of working medium is transferred in condenser to a process e.g. long-distance heating net, heating, cooling tower. Working medium is completely condensed. After condensation, it is guided to feed pump [21].

Compared to competing technologies, ORC has several and important advantages. Firstly, this cycle has high cycle and turbine efficiencies. Because of the low peripheral speed, mechanical stress of turbine is low. Moreover, low RPM of turbine allows the direct drive of the electric generator without reduction gear. ORC also has very long operational life and low maintenance cost. There are also other advantages, such as simple start – stop procedures, quiet operation and good partial load performance [22].

However, there are some disadvantages of ORC. First of all, ORC is not suitable for high temperature process heat production and large power plants. Additionally, a disadvantage in principle of the ORC technology is the relatively small electrical efficiency. Because of low temperature, efficiency can be reached, which amounts to approximately half of a water vapor process [23]

2.3.2 Working fluids for ORC

The selection of the working fluid is of key importance in Organic Rankine Cycles. Due to the low temperature, heat transfer inefficiencies impair to the efficiency highly. These inefficiencies depend very strongly on the thermodynamic characteristics of the fluid and on the operating conditions. The parameter or characteristics of fluid at below are considered for selection of fluid for ORC.

- Isentropic saturation vapor curve: Since the purpose of the ORC focuses on the recovery of low grade heat power, a superheated approach like the traditional Rankine cycle is not appropriate. Therefore, a small superheating at the exhaust of the evaporator is always preferred, which has consequences on the optimal thermodynamic properties of the fluid. The saturation curve in the Ts diagram can have a positive, negative or vertical slope. Moreover, the critical temperature of the fluid should be (10 -20 K) of the maximum inlet temperature of the heat source but this difference must not be high.

- Freezing, boiling and stability temperature: The freezing point has to be lower than the lowest temperature in the cycle because in the cycle working medium has to be liquid or gas phase. Also, the fluid should be liquid phase at ambient condition. This is necessary to avoid escaping volatile gas to environment. Organic fluids usually suffer chemical deteriorations and decomposition at high temperatures. The maximum hot source temperature is thus limited by the chemical stability of the working fluid.
- Heat of vaporization and density: A fluid with a high latent heat and density will absorb more energy from the source in the evaporator and thus reduce the required flow rate, the size of the facility, and the pump consumption.
- Environmental impact: Effect of working medium to environment has to be low. The main parameters are the ‘ozone depleting potential’ and ‘greenhouse warming potential’.
- Safety: The fluid has to be non-corrosive, nonflammable, and nontoxic. Depending on the location of the facility, this parameter can be of very high importance.
- Good availability and low cost: Traditional refrigerants used in ORC are expensive. This cost could be reduced by a more massive production of those refrigerants, or by the use of low cost hydrocarbons.
- Acceptable pressures: Very high pressures have a negative impact on the reliability of the cycle. They lead to the need of more resistant and more expensive facilities [19, 21].

2.3.3 Operational areas of ORC

Because of usage organic oil with lower boiling temperature, useful energy can be produced at relatively low temperatures (70–300°C). Three main categories of applications are conceivable for the Organic Rankine Cycle. Many ORC plants have been installed in geothermal power stations and a few ORC generators are in operation with industrial waste heat. Also, Usage of ORC system in solar thermal power station has increased recently.

- Waste heat recovery: Where the ORC is most useful is in the recovery and use of waste heat. Two primary applications include Combined Heat and Power plants (especially those utilizing biomass as fuel), and general heat recovery applications

from many potential sources. A combined heat and power plant can for example be a small scale cogeneration plant on a domestic water heater. Heat recovery can also be performed on industrial or farming processes such as organic products fermentation, hot exhausts from ovens or furnaces, exhaust gases from vehicles, intercooling of a compressor, condenser of a power cycle, etc.

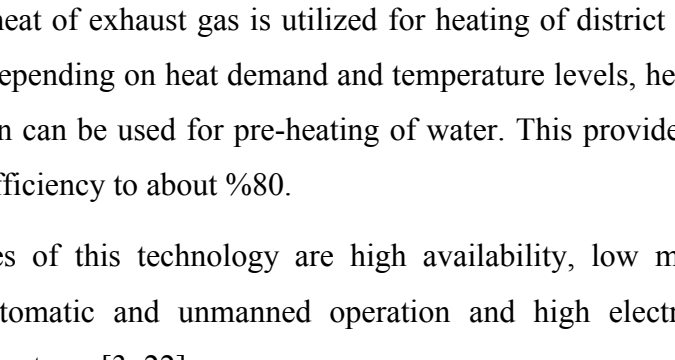
- Solar thermal power: Organic Rankine cycles can be used in the solar parabolic through technology instead of the usual steam Rankine cycle. The ORC allows a lower collector temperature, a better collecting efficiency (reduced ambient losses) and hence the possibility of reducing the size of the solar fields.
- Geothermal plants: Geothermic heat source vary in temperature from 50 to 350°C. For low temperature geothermal sources (typically less than 100°C), the power plant efficiency is very dependent on the ambient temperature, that determinates the heat sink temperature [19].

2.3.4 Biomass fired CHP plants based on an ORC

Production of electricity from biomass with ORC is relatively small generation units. Biomass fuel is supplied from a single source or a number of sources in a limited area. Therefore, a complex biomass gathering organization and the additional commercial, transport and storage cost can be minimized.

An example of biomass fired CHP plants with ORC is showed in Figure 2.12. m_1 and m_2 are fuel and air inlet respectively. Also, m_3 is flue gas exit. Q_1 and Q_2 are heat for district heating and P is electricity output. Biomass is combusted in furnace or combustor that equipped with filters controls, automatic ash disposal and biomass feed mechanism etc. Hot thermal oil is utilized as heat transfer medium. Thermal oil is heated in an atmospheric liquid tube boiler. There are advantages of usage of thermal oil. These are low pressure in boiler, large inertia and insensitivity to load changes, simple and safe control and operation. Also, the adopted temperature (about 300°C) for hot side ensures a very long life of the oil.

An Organic Rankine Cycle is used to convert thermal energy to electricity. Due to the low temperature level, the organic oil used in the ORC is heated in a secondary circuit by thermal oil in the evaporator. Heat of organic liquid is converted to mechanical energy by turbine in ORC and generator, which produces electricity, is directly connected to turbine. The condensation is used for hot water at about 80-



tionally, heat of exhaust gas is utilized for heating of district heating sy-

completely automatic and unmanned operation and high electric efficiency for biomass CHP systems [3, 22].

ORC is commonly used in geothermal power plants but there have been developments biomass fired ORC plants. These plants are operated or constructed in

ORC is commo

are considerably lower than for a comparable steam plant. Additionally, hence ORC is fully automatic system; labor cost of this cycle is lower [3, 22]. A study was made

for economical evaluations of biomass plants based on ORC that has electrical capacity from 0.4 MWe to 1.5 MWe. According to this study, the cost of the produced electricity depends on the additional costs and produced energy that has been analyzed two key parameters; cost of biomass fuel [Euro/MWh] and equivalent full load operating hours [hours/year]. The cost of the biomass has been varied between 0 and 3.5Eurocent/kWh heating value and the full load operating hours between 2000 and 8760 hours/year. Cost of electricity decreases with increase full load operating cost and produced energy also it is proportional to fuel cost.

ORC for biomass, where silicone oil is utilized as working medium, has a net electric efficiency of about 18% when condensation is operated. About 79-80% is discharged as cogenerated heat to the cooling water. The thermal and electric losses are determined as only 2-3% for ORC. Moreover, ORC unit can be operated at partial as low as 10% of nominal load and partial load efficiency can be up to 50% nominal load efficiency.

The thermal oil boiler and presence economizer is affected to efficiency of the overall plant. Thermal oil efficiency can be between 75 and 80% and with modern thermal oil boilers provides that overall electricity can reach to above 14%. In the plant with economizer, thermal efficiency can be increased to about 90% [3].

2.3.6 Literature review study

In this section, some of studies about biomass CHP plant, ORC module and biomass fired CHP plants based on an ORC are briefly summarized.

Gard studied about literature review of small-scale biomass CHP technologies in his master thesis. Used technologies in power generation from combustion and gasification are explained with economic evolution. Moreover, details information of practical application of each technology is given. An economic comparison was made between these plant application and cost of electricity was calculated by using annual operational hours, fuel price, interest rate and economic lifetime for the different plants [24].

Operational Organic Rankine Cycle is analyzed with its advantages, drawbacks, and possible applications in Quoilin's study. An experimental study is carried out on an ORC recovering heat from hot air at a temperature ranging from 150 to 200°C. The expander used for this study is a volumetric scroll expander. The working fluid

selected is R123 because of its high efficiency in ORC applications. The limits of the cycle are investigated by modifying some parameters of the test bench. A model of each component of the cycle is proposed and validated. The whole cycle is simulated in order to have a good understanding of its behavior under different working conditions [19].

Schuster, Karellas, Kakaras, Spliethoff studied about energetic and economic investigation of Organic Rankine Cycle applications. In this study the state of the art of ORC applications such as biomass combustion and geothermal plant is presented and also innovative systems that include solar desalination, waste heat recovery and micro CHP are investigated. Innovation systems are simulated a process simulation environment using experimental data. The results of the simulation like efficiencies, water production rates or achievable electricity production cost are discussed [25].

Wei, Lu X., Lu Z. and Gu made dynamic modeling and simulation of an ORC system for waste heat recovery. This study proposes two alternative approaches for the design of a dynamic model for an Organic Rankine Cycle (ORC) to be used for the design of control and diagnostics systems. The model has been developed in Modelica language and simulated with Dymola. The two modeling approaches, based on moving boundary and discretization techniques, are compared in terms of accuracy, complexity and simulation speed [26]

Erhart studied about setting up a model ORC in his master thesis. The aim of this work is improvement of efficiency of ORC. In this study, Operation, economical situation and efficiency of ORC are depicted. Also, running different load scenarios of this model is investigated and calculated results are compared to the monitored data. Several suggestions are given to improve efficiency of ORC [21].

ORC plant for power production from biomass that has capacity between 0.4 and 1.5 MWe are researched in Duvia and Gaia's study. Technology, efficiency, practical experience and economical analyzes of each plants which has different capacity are compared. Cost of electricity is evaluated according to cost of biomass and equivalent full load operating hours for each capacity [22].

A project, which was implement by Neuner, is about energy supply system in Admont, Styria, Austria. The plant supplies a wooden and furniture company with process and space heat and the Benedictine monastery of Admont with space heat

from biomass and ORC module covers almost half of the electricity demand of the company. In this study, the reduction of NO_x and dust emissions are purposed and innovative technologies are tested and effect of these technologies on emissions are considered [27].

Obernberger, Thonhofer and Reisenhoser studied about biomass CHP plant based on ORC in Lienz Austria. In this study, operation, safety aspects, process control of this plant is explained and operating condition of ORC is optimized. Economical and environmental evaluation are made by this project team. Moreover, application potential and future development targets are expressed [28].

Three papers about CHP plant in Scharnhauser Park are published by Strzalka, Ulbrich and Eicker. One of them contains energy supply system of Scharnhauser park and operation of this CHP plant are explained [29]. Another study of this plant is analyzed during the first four years of operation and effect of fuel properties and fly ash are investigated [30]. In the paper is named as ‘energy and environmental performance of a biomass cogeneration plant in an urban area’ partial load efficiency and environmental effect with NO_x, CO and particulate emissions of this biomass plant are considered [31].

2.4 The Energy Supply System of Scharnhauser Park CHP Plant

Scharnhauser Park is located in Stuttgart – Ostfildern. There are individual area and public building in this district. The energy that is needed to Scharnhauser Park is supplied by an environmentally friendly, sustainable way. Each year 80% of the heating and approximately 50% of the electrical power for the area Scharnhauser Park are produced CO₂ neutrally in the CHP plant [29]. Total energy demand in Scharnhauser Park and heat and electricity production of CHP plant are tabulated in Table 2.2 [30].

Table 2.2: Energy production of the CHP plant in Scharnhauser Park [30]

Year	Demand [MWh]	Biomass heat [MWh]	Biomass share [%]	El. ORC [MWh]
2004	19899	10802	54.3	1103
2005	23306	17220	73.9	1212
2006	24255	19716	81.3	278
2007	23544	19441	82.6	3308

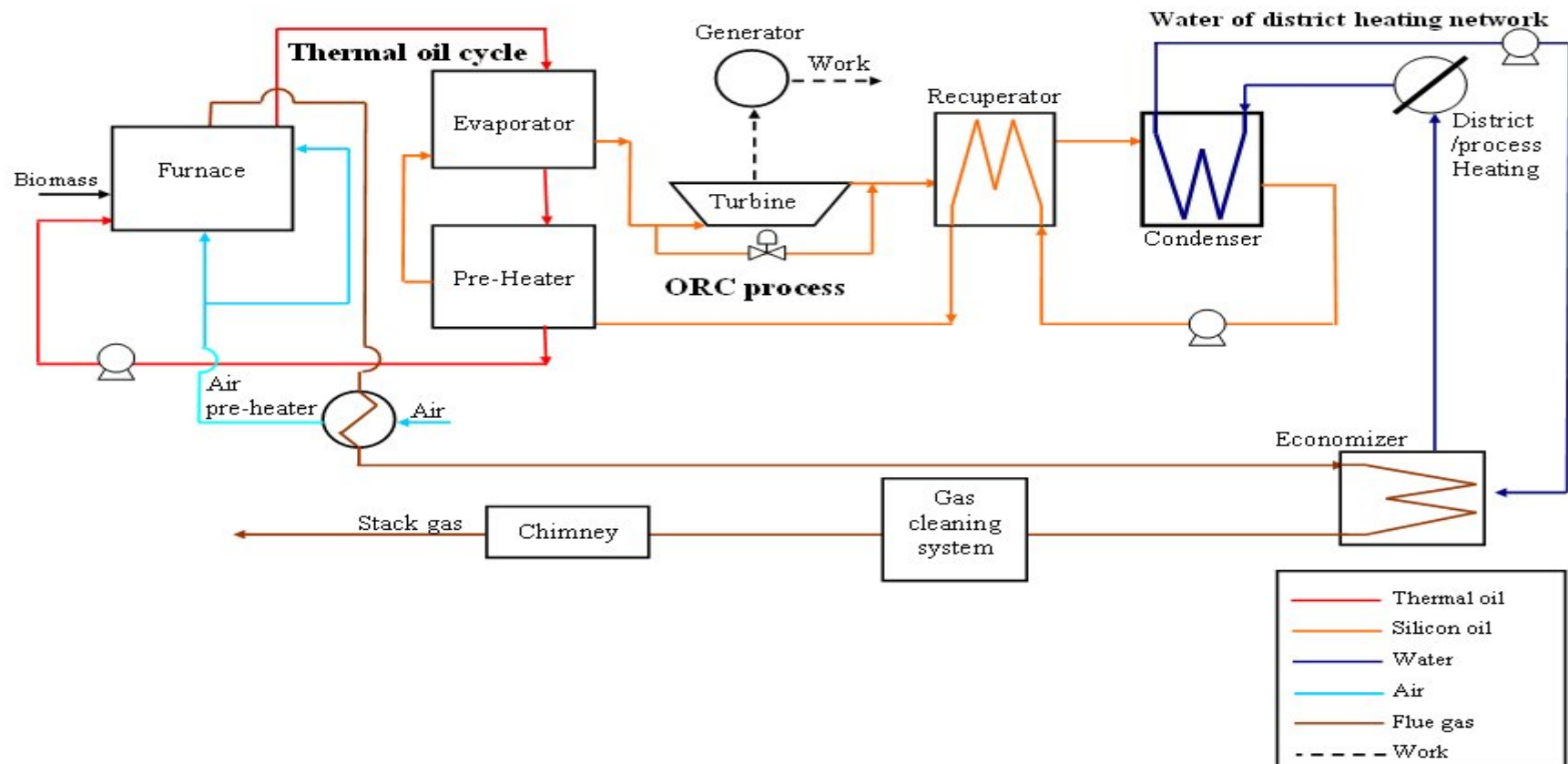


Figure 2.13: Flow chart of CHP plant in Scharnhäuser Park

A combined heat power plant (CHP) covers almost heat and electrical energy demand of this area. Flow chart of this CHP plant is shown in Figure 2.13. Energy from biomass is produced with high efficiency and low emissions by that CHP plant. Some technical data of this biomass plant is given in Table 2.3.

Table 2.3: Technical data of this biomass plant [31]

Thermal power furnace	6000 kW _{th}
Electrical power ORC	1000 kW _{el}
Thermal power ORC	4650 kW _{th}
Capacity of wood storage	1400 m ³
Wood consumption full power	200 m ³ /day
Annual wood consumption	63.000 m ³ /year
Fossil fuel savings	~40mill. kWh/year
Reduction CO ₂ emissions	~7.000 tons/year

For energy generation, natural wood scraps and forested wood are burned in this plant. The wood has water content of 65% and the fuel value achieves 0.70 MWh/m³. The plant is equipped with a firewood bunker with a holding capacity of 1000 m³. The fuel is automatically carried hydraulically to the burner [31].

Plant efficiency of the CHP plant in Scharnhauser Park is tabulated in Table 2.4. Degrees of efficiencies for most combustion systems are computed as 70 and 80%. The overall efficiency degree of Scharnhauser Park CHP plant is calculated as 82.38%. This value can be described as relatively high in respect of those reference values.

Table 2.4: Plant efficiency [30]

Combusted wood chips	135376 m ³
Fuel value	0.70 MWh/m ³
Fuel energy	94768 MWh
Generated energy (heat + electricity)	73456 MWh
Overall degree of efficiency	82.38 %

2.4.1 Operation of the CHP plant in Scharnhauser Park

This biomass furnace is the core of the plant shown in Figure 2.14 [30]. The capacity of furnace is 6 MW_{th}. This modern feed grate firing is equipped with a fully automated control system, which makes a clean and complete combustion possible. Also, this control system ensures a minimum appearance of the pollutant emissions.

The burning chamber of the furnace is built as a counter flow chamber. This type of furnace is suitable for burning of freshly harvested biomass with a moisture content of up to 65%. [29]. The combustion chamber contains two different zones. Optimization of wood thermal utilization is provided by this way. The fuels are gasified under sub-stoichiometrical conditions in the primary combustion zone where drying, devolatilization, gasification and char combustion occur. The gases which are produced in the primary combustion zone are transferred to the secondary zone. In this zone they are burned under over-stoichiometrical conditions [30].

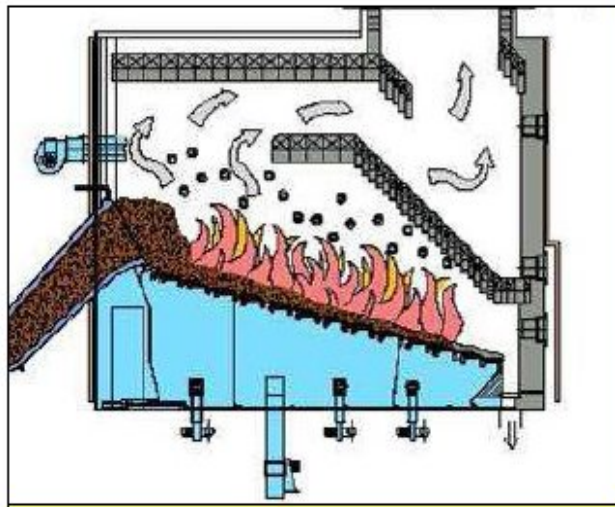


Figure 2.14: Biomass furnace at CHP plant in Scharnhauser Park [30]

The heat that is produced in the furnace is transferred to the evaporator of the ORC cycle by thermal oil. The advantage of thermo oil usage is that there is no utilization of steam boiler for electricity production. Therefore operation of the plant can be easier and above all more economical.

The plant in Scharnhauser Park includes Organic Rankine Cycle (ORC) module that produce heat and electrical energy. An ORC module showed in Figure 2.15 uses a heated chemical as working medium instead of steam as found in the Rankine Cycle. Silicon oil (MDM) is utilized as the working medium in Scharnhauser Park CHP plant. The use of silicone oil has advantage that electricity can be produced at lower temperature and pressure. Operating and personal cost of ORC module can be lower [31].

Silicone oil in CHP plant of Scharnhauser Park that is approximately 100% pure substance is produced by Dow Corning. Its chemical name is Octamethyltrisiloxane or abbreviated MDM or OMTS. This organic liquid is a non polar chain of three

siloxo-groups saturated by eight methyl-groups. Surface tension of MDM is quite low and it can evaporate quickly. Decomposition of silicon oil starts at 300°C. This substance is almost non-toxic and is utilized as solvent and matrix in cosmetic industrial. Also, silicone oil is harmless for the ozone layer [21].

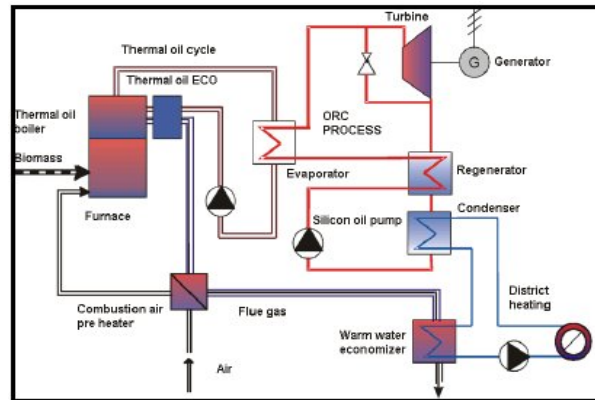


Figure 2.15: ORC Process [31]

Thermo oil heat is given to silicon oil in evaporator where the silicon oil is vaporized. After evaporation, the vapor of silicon oil is sent to the turbine where the thermal energy of the steam is converted to mechanical energy. A single stage radial turbine is used in this cogeneration plant. A generator with electrical capacity of 1MW_{el} is directly connected to turbine. The electric efficiency of the ORC is calculated as about 18% and this value is high value for small-scale-CHP-plants.

Silicon oil is guided to recuperator and then condenser. The heat of working fluid that is waste heat from electric generation is transfer to liquid MDM in recuperator. Afterwards the residual heat of silicon oil is transferred to water of district heating network in condenser. After condensation, liquid MDM is pumped to recuperator again and it reaches to evaporator.

Water that leaves from condenser is consigned to economizer. In this equipment, the residual heat of fume whose heat is firstly given to air for pre-heating is removed to district heating network. The exhaust heat recovery ensures to increase of overall efficiency and decrease of environmental impact [21, 30]. The exhaust heat recovery allows fuel consumption degrees of over 80% [30]. After exhaust heat recovery system, the flue gases enter a complex exhaust gas cleaning system. This system provides to reduce dust particles significantly. Moreover, for control the emissions of pollutants in fume a permanent emission monitoring system was built [29].

2.4.2 Environmental impact

Generally, biomass combustion is considered to contain complete oxidation whose reaction products are H_2O and CO_2 . However, the flue gas can include undesirable pollutants. In a process with poor control systems, quantities of these substance increase in flue gas. Emission values can be decreased by using advanced biomass combustion process.

The emission values, showed in Table 2.5, can be utilized as reference values for the assessment of measured emission values in Scharnhauser Park CHP plant. These values are emission of central heating system whose primary energy comes from biomass.

Table 2.5: Average emission values for biomass furnaces (50-100 kW) [31]

Parameter	Emissions in mg/Nm^3	
	Wood chip boiler	Wood pellet boiler
CO	95	32
C_{total}	2	1
NO_x	123	123
Particles	27	24

Exhaust heat recovery and exhaust gas cleaning system allow the significant reduction of emission at CHP plant in Scharnhauser Park. The emission limit values and the emission measurement results of this plant are tabulated in Table 2.6 [31].

According to tables at below, all measured emissions values are lower than the limit values for biomass combustion. And also, these measured values are lower than emission values of wood chip and wood pellet boiler.

Table 2.6: Permitted and measured emission values for CHP Scharnhauser Park [31]

Parameter	Emissions in mg/Nm^3	
	Emission limit values	Measured emissions
CO	150	8.1
C_{total}	10	0.15
NO_x	250	199
Particles	20	6.1

2.4.2.1 NO_x emissions

The operation of biomass furnace with two stage combustion allows reduction of NO_x emissions. Additionally, because of exhaust heat recovery system, the flue gas is slowly cooled and NO_x decompose to N_2 and O_2 . The measured NO_x emissions are higher than the references values (Table 2.5) because the fuel of CHP plant in

Scharnhauser Park includes undesirable fuel like grass. The burning of herbaceous biomass that contains high nitrogen creates high emissions of NO_x . The NO_x emission of herbaceous is measured as 478 mg/Nm^3 [31].

2.4.2.2 CO emissions

The improvement of complete combustion provides low emission. The secondary air injection in furnaces is important operation for the combustion system and this allows good mixing of combustion air with combustible gases in the furnace. The complete combustion ratio increase with good mixing of these gasses. Consequently, the concentrations of unburnt pollutants can be reduced to levels close to zero [30].

A measuring system for a continuous monitoring of CO emissions is installed in the plant in Scharnhauser Park. The CO emissions measured in one day are showed in Figure 2.16. These emission values were calculated with a reference oxygen content of exhaust gases of 13% [31].

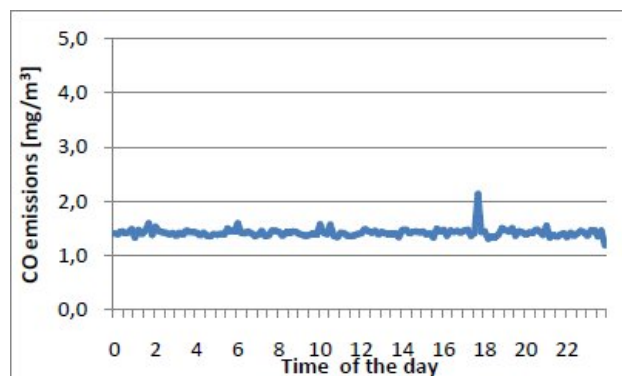


Figure 2.16: CO emissions (at 13 vol% O₂) [31]

The CO emissions of Scharnhauser Park CHP plant are measured lower than average emission values for biomass furnaces as shown in Table 2.5. Besides, this value is lower than the limit values for biomass combustion (Table 2.6).

2.4.2.3 Particulate emissions

The particulate emission is very important parameter for the environmental impact of biomass combustion. The decreasing of particles smaller than $10 \mu\text{m}$ (PM₁₀) is important entailment because severe health problems are caused by these particles with being inhaled. [30].

The plant in Scharnhauser Park is equipped with a multicyclone and an electro filter that remove the particles. Moreover, particulate emissions are controlled by using a

continuous monitoring system. Therefore, significant reduction in particulate emissions can be achieved. Therefore the measured emission values are relatively lower than emission of particles permitted value as shown in Table 2.6. Also, if particulate emission of this plant is compared to reference values in Table 2.5, the measured emission values are relatively low [31].

2.5 Simulation Programs

A computer simulation is a computer program or network of computers that assay to simulate model of special system. Simulation is ‘the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system’. [32]

Simulation is an effective tool if it is operated and understood thoroughly. In industry and academia, simulators provide a considerable function because simulation programs have several advantages. The most important advantage of simulators is that accordance and efficiency of system can be determined by the system simulation before this system is practically constituted. This allows utility of alternative designs is investigated without construction of the system. Even as design stage, the effect of important decision can be analyzed owing to simulation program. Therefore, the overall cost of system can be decreased. One of the advantages of simulator is that study a problem at various distinct level of abstraction. The behaviors and coactions of the high level components can be better able to understand. Another benefit is employability as educative means to students for illustration or training. The behavior and relationship of the system's components can be shown by simulation so the real system is understood meaningfully.

Simulators have some defects, although they have important advantages. Some simulation programs ascribe many of these problems to the computationally intensive processing. The results of the simulation may not be readily available after the simulation has started - an event that may occur instantaneously in the real world may actually take hours to mimic in a simulated environment. As a result, limitation of hardware platforms which cannot meet the computational demands of the simulator restrict to these simulators. Nevertheless, this problem is becoming less of

a concern with more powerful platforms and advantaged simulation techniques. One of struggle ways of this complexity is that simplifying assumptions or heuristics into is made the simulator engine. [33]

The reliability of computer simulations influences the validity of the simulation model, so for verification is very important development of computer simulation. Besides, reproducibility of the results is another important aspect and it means that different answers should not be provided by program for each execution.

As a conclusion, computer simulations have become a useful part of mathematical modeling of many natural systems in all discipline such as physics, chemistry and biology, economics, psychology, social science and the process of engineering new technology [34].

2.5.1 Power plant simulation

Software for modeling and simulation of energy processes has been developed sharply for the last ten to twenty years. The exact information about energy systems behavior is needed for link with a higher degree of integration and optimization of processes, becoming closer to the limits of the material strength on account of temperature, pressure, or dimensions, and control of the processes [35].

Software tools (often equation base) are utilized due to supplying of this information under construction and making decision in varies stage of operation [36]. These tools with extendible component library may be applied for steady state or dynamic simulation or both of them [35].

Steady-state solvers use equations for defining the relationships between elements of the system and finding a state such as comprises the pressure, temperature, flow, enthalpy and fluid composition at equilibrium condition. Process connections and equipment specific parameters can be the input values of the model. The steady state simulation point out how variations in the process concept and parameters affect on the performance of the plant [36].

Direct outside influence cannot be changed on variables for dynamic systems and their values will also depend on earlier applied signals [37]. For a plant scale dynamic simulation the input data is process connections, physical dimensions of

process equipment, equipment specific and control parameters, automation concept diagrams and the initial condition [36]

For power plant simulation, there are two approaches: One of them is that mass- and energy balances are solved in a flow sheeting simulation tool. And also, for the modeling of single units dedicated models are developed. Heat and mass balance commercial software packages are commonly available on the market. Some of them that can be used for simulation for power plant simulation are described below.

Aspen Plus is steady state solver for chemical processes and this program is often utilized in gas turbine applications. It uses a sequential solver.

Camel may be applied for both steady state and dynamic simulation. The solver of this program is sequential method.

Code written by Consonni is suitable for steady state simulation of different type of gas and steam turbine system.

Cycle Tempo, which is a steady state solver, can be used for power and refrigeration systems. The solver of the program is a mixture between sequential and simultaneous methods.

DIMAP is developed for studies of different steady state cycle. The program has a sparse matrix Newton solver.

DNA can be performed for both steady state and dynamic simulation. The system of equations is solved by Newton solver and it has a sparse linear equation solver. A fourth order Backward Differential Formula (BDF) method uses to solve the differential equations.

Dymola is suited for dynamic system simulation. It has several standard solvers for Ordinary Differential Equation (ODE), Differential Algebraic Equation (DAE) and handles discontinuities efficiently. This program is not widely used for energy system simulation. The language of this program is developed for energy system.

EES is applied for steady state system and the program has Newton solver. Although it can be utilized for dynamic simulation, efficiency has been limited by implemented ODE solver.

ESMS uses a specially implemented simultaneous linear equation solver for simulation of steady state process.

GT Pro is applied for steady state simulation of power plant. The solution method of this commercial program is sequential in the equations.

Gate Cycle is a commercial simulator for steady state simulation of power plants. It uses a sequential solution method.

Hysys, which is a commercial program, uses a sequential solution method. It is developed for chemical process. It can be utilized for both steady state and dynamic simulation.

ICAS can be applied for steady state and dynamic simulation. This highly integrated software package is used for analysis of chemical process plants [35].

IPSE Pro can be used for energy and chemical engineering application [38]. It uses Newton based gradient solver to calculate steady state solution [39].

MSS/ACSL is a commercial program for simulation of dynamic systems. ACSL is modeling language with MSS graphical extension. The solver of program is a sequential method.

Matlab/Simulink is a commercial simulator for dynamic system. The program has several solvers for ODE systems [35].

Prosim includes an iterative Newton – Raphson gradient based solver for steady state simulation. [39].

Vissim is simulator for dynamic systems in general. It includes several solvers for ODE system

Windali is developed for dynamic system simulation. It uses several standard DAE solvers [35].

2.5.2 Description of IPSEpro program

"IPSE" originally stood for 'Integrated Process Simulation Environment'. At that time in the early 1990s IPSE could be used as a standalone program. The suffix "pro" was added when it was separated to the two distinct modules [40]. IPSEpro, is a software package, is developed by Sim Technologies in Austria. This program is flexible and extensive simulator and it is used for analysis and modeling of energy and chemical engineering areas. It has Newton based gradient solver for calculation the steady state solution [38, 39].

Models of a process can be created using by standard library components or component models which is built by user [38]. Four standard libraries are being offered by SimTech. These are power plant, gas turbine, refrigeration and desalination. Physical properties of components for conventional power plants, cogeneration power plants and combined cycles etc are found in the power plant library and also new properties are added by user [39].

IPSEpro includes two modules that are called MDK (Model Development Kit) and PSE (Process Simulation Environment). For creation and modifying of model library, MDK is utilized. Process models based on a library's component models are set up with PSE. Component models describe mathematically the system components behavior. This mathematical description is based on equations and different other items like variables and parameters [38]. Interaction of IPSE pro's modules is shown in Figure 2.17 [21].

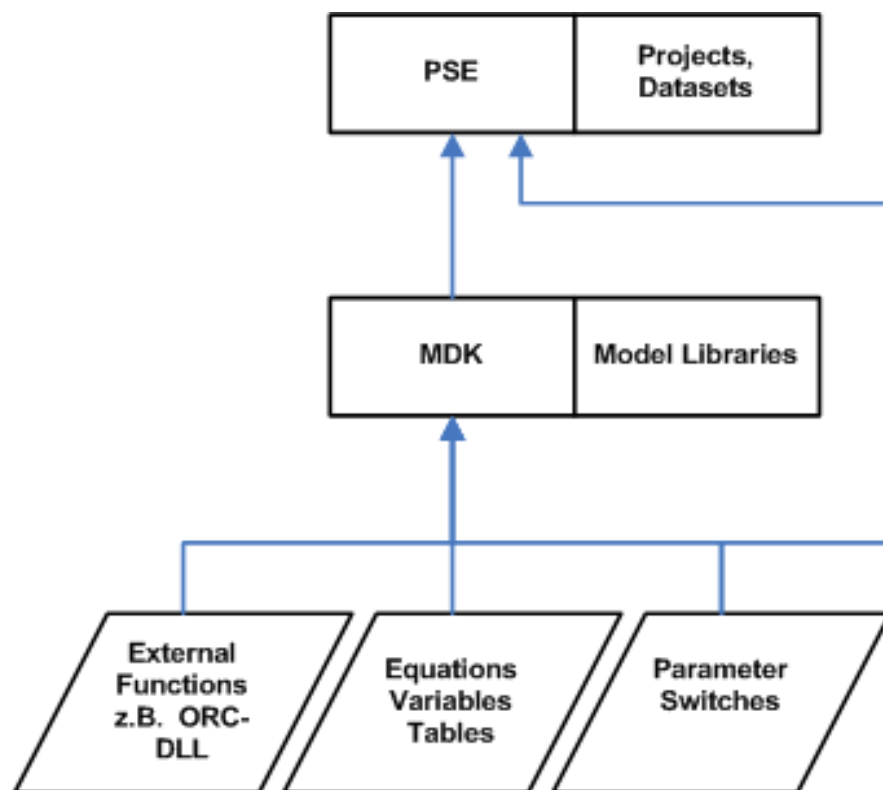


Figure 2.17: Program structure of IPSEpro [21]

The competent definition of the data flow is achieved owing to the division of these modules in IPSEpro. Generally, more than one project can make use of a model library. When a process model is built without need of change of the library, the user can use only PSE. Therefore, accidental changes of the library obstruct.

IPSEpro separates three types of process component. According to this structure; objects can be only referenced by other object at higher hierarchical level. Figure 2.18 show that interactions between each other of these object types [21, 38].

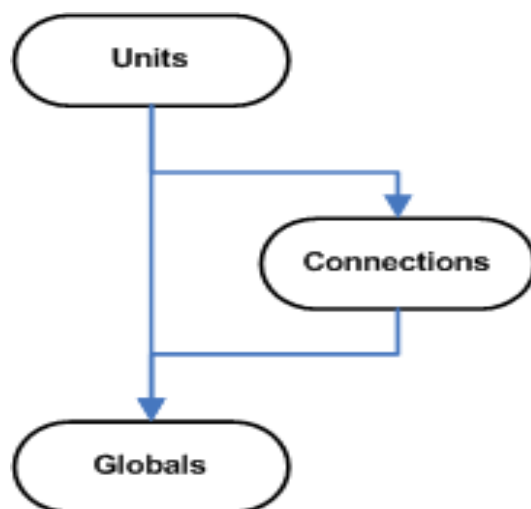


Figure 2.18: Hierarchy of the model classes [21]

The nodes in the network structure are called as unit. Generally, units symbolize substantial part of equipment. All other types can be referenced by these objects but they can not reference each other. Information that is transferred between two units is represented by connections. These objects can reference globals, but can not reference units or other connections.

Globals give information that is shared by an undefined number of other objects. These objects do not directly depend on the network structure. A chemical composition is a typical example for a global can be shared by more than one streams use this composition. Although all other objects types can reference globals, others can not be referenced by globals.

All information of models for these tree types of objects is stored by IPSEpro in model library. Before working on a project, the model library that will be used for the project must be selected. The model library can be installed explicitly or implicitly.

Graphical icon represents the unit models from a model library. These icons can be located on the drawing area in PSE module and must be connected to each other. The equations and variables of all components into one system of equations are combined by way of connection of component models on the flowsheet. In this way, the mathematical model of the process is set up in PSE.

Variables and parameters of each component model are revealed by this component model on its interface, in order that other object of project can utilize its valid variables and parameters. Variables and parameters are two types of items that items that are utilized for mathematical definition of a model. This means that numerical data of a model is represented by both of them. A parameter expresses a constant value that is never computed during solution of system. Therefore, parameter value must be inserted and is necessity for a component model description at all times. A variable represent as an unknown characteristic of the system. The value can be inserted by user or calculated by solver [38].

IPSEpro is a COM-based software so that it can be connected with other software. This is one of the advantages of IPSEpro. Another advantage of this program that is the user can change of standard library or even build new one with MDK. Moreover, IPSEpro has short calculation time that is a major advantage of this software package. On the other hand, if an error takes place, discovering of this error on calculation log file can be difficult [39].

3. SIMULATION STUDY

A program is developed with IPSEpro in order that ORC module of the CHP plant in Scharnhauser Park is simulated. This program calculated power generation by using real data of this plant. The aim of this study to make the deviation analysis by comparison calculated and measured power generation and controlling of suitability IPSEpro with ORC module in Scharnhauser Park CHP plant.

3.1 Simulation Study with IPSEpro

In this studying, twenty eight data groups, which were taken from the Scharnhauser Park CHP plant on 16 November 2007, were utilized. Each seventh data group is average of six points that is previous of itself. Power generation was calculated by IPSEpro. The aim of this study is making deviation analysis by comparison calculated and measured power generation and controlling of congruity IPSEpro with ORC module of CHP plant in Scharnhauser Park.

Existed ORC library was utilized for model library in that program. The library for ORC was especially developed by Bergmann S. and Erhart T. G. for ORC module simulation. The used components are modified aggregates from the standard application library [41]. Consequently, creation of a new library or modifying library with MDK was not developed for this study. In other words, this program was developed using by only PSE.

The global objects depend on model library that are used. MDM, Therminol66 and water were defined as global objects. Therminol66 is thermal oil and was called as TO in the program. A global object is added by using the command New Global Object from the objects menu. If global object is edited or deleted, the command Edit or Delete Global Object from same menu is selected [38].

After units or equipments of ORC module were placed in the interface of IPSE, these units were connected. In this study, twenty eight data groups were used. In this report, setting up phase of program is explained with only one data group (point 7)

that is average of first six data group. Variables that were taken from the Scharnhauser Park CHP plant of all points are tabulated in Table A.2 (Appendix A2) and also parameters of the program are tabulated in Table 3.1. Variables and parameters of all units and their connections that were used into the program are given below.

Table 3.1: Parameters of the IPSEpro program [21, 41]

Pre-Heater	Δp_{cold} (bar)	0.1	Generator	eta	0.9599
	Δp_{hot} (bar)	0.1		eta_m	1
	Heat loss (%)	2	Recuperator	Δp_{cold} (bar)	0.5
Evaporator	Δp_{cold} (bar)	0.1		Δp_{hot} (bar)	0.04
	Δp_{hot} (bar)	0.1		Heat loss (%)	2
	Heat loss (%)	2	Condenser	Δp_{cold} (bar)	0.2
Pipe	Δp_{cold} (bar)	0.1		Δp_{hot} (bar)	0.01
	$\Delta T(^{\circ}C)$	0	Pump	eta	0.75
Turbine	eta	0.78		eta_m	1
	eta_m	1	Motor	eta	0.98
				eta_m	0.98

MDM that comes from regeneration is sent to pre – heater. Inlet MDM stream's temperature is estimated as 166°C that was measured value. The variables of connection of pre heater, which are set, are temperature and pressure of outlet thermal oil stream. These values are 3 bars and 227.7 °C. Actually, pressure of this stream is not available in measured data. This pressure is about as 3 bars so it is assumed [41]. Pressure differences of cold and hot streams are 0.1 bars [21] and heat loss is assumed as 2%.

For evaporator, pressure differences of cold and hot streams are inserted as 0.1 bars [21] and heat loss ratio is assumed as 2%. These values are the parameters of evaporator. Only temperature of inlet stream of thermal oil that is a variable of connections is given as 283.8. Before turbine, MDM passes through the pipe in the program. Pressure difference is assumed as 0.1 bars. Another assumption about pipe is no temperature difference.

A single stage radial turbine, which is manufactured by Tuthill – Nadrowski, is used in ORC module of Scharnhauser Park plant. The efficiency of the engine is 78% for all range of operation at the single stage design and the constant revolution speed. In this program, efficiency and mechanical efficiency of turbine are 0.78 and 1 respectively [21]. These values are parameter of turbine. Temperature and pressure

of inlet connection are inserted as 259.7 °C and 7.3 bars. At outlet stream, temperature and pressure are 221°C and 152 mbar but temperature value is only estimated.

Manufacturer of generator is Weier Electric, Eutin. At a constant speed of 3000 RPM maximal nominal electric power output is delivered as 15000 kW. Mechanical and electrical efficiency of synchronous engine are enrolled as 1 and 0.9599 [21].

Recuperator is produced by Tubetech GmbH and heat transfer ratio of recuperator is given 77% by manufacturer. Parameters of this unit are pressure differences of hot and cold stream and these values are 0.04 and 0.5 bars respectively [21]. All connections variables of this unit were not determined except temperature of cold stream and also this value is only estimated as 166 °C.

After regeneration, MDM (hot stream) is guided to condenser. The residual heat passes through water of district heating network. Pressure differences of water and MDM are defined as 0.2 and 0.01 bars [21]. Measured temperature inlet and outlet water stream are 56 and 72 °C. Although, the data that are taken from Scharnhäuser Park CHP plant do not contain the pressures of water streams, pressure of inlet stream is known as about 3.2 bars [41]. For that reason, this value is assumed as 3.2 bars for all data group. The temperature of MDM inlet stream is set as 121 °C. Outlet stream's pressure and temperature are only estimated 0.1 bars and 76 °C.

After the condensation, MDM is pumped to regeneration as cold stream. Parameters of pump are efficiency and mechanical efficiency of pump is 0.75 and 1 respectively. Volumetric flow rate of inlet stream is given as 78m³/h. Specific volume of MDM is determined by using another program of IPSE pro at given temperature and pressure. Mass flow rate was calculated as 16.95 kg/s by using these values. Specific volume and mass flow rate for all point are tabulated in Table 3.2. Efficiency and mechanical efficiency of motor are entered as 0.98. Subsequent stage of regeneration is pre heating.

Table 3.2: Specific volume and mass flow rate of MDM at inlet stream of pump

Point	Specific Volume (kg/m ³)	M _{mdm} (kg/s)	Point	Specific Volume (kg/m ³)	M _{mdm} (kg/s)
1	0.001278	17.61	14	0.001279	15.64
2	0.001277	16.75	15	0.001278	13.69
3	0.001279	16.94	16	0.001279	12.81
4	0.001278	16.72	17	0.001278	13.48
5	0.001279	16.72	18	0.001278	13.48
6	0.001278	16.52	19	0.001277	13.70
7	0.001278	16.95	20	0.001278	13.26
8	0.001277	15.23	21	0.001278	13.48
9	0.001281	15.18	22	0.001285	17.08
10	0.001278	15.43	23	0.001288	17.68
11	0.001279	15.42	24	0.001287	17.48
12	0.001281	16.26	25	0.001288	16.39
13	0.001281	15.61	26	0.001290	17.44
14	0.001279	15.64	27	0.001288	18.12

These units and their variables and parameters, which are defined, were used for developing of the system.

3.2 Pressure vs. Enthalpy Graphs of ORC Module

Due to observation of enthalpy change of ORC module, enthalpy vs. pressure graph was plotted by using Excel sheet based on Visual Basic that exist in SENCE department of HfT Stuttgart University. Moreover, phase change of MDM was observed with this graph and according to phase change, suitability of the simulation by IPSEpro was evaluated.

For this graph, temperature and pressure of each MDM stream are used and these values are set values of IPSEpro or calculated by this simulation program. Pressure and temperature values of MDM for point 7 are tabulated in Table 3.3. These values for other points are appeared on IPSEpro flowsheet of ORC in Appendix A3.

Table 3.3: Inlet properties of equipments for point 7

Equipment	Temperature (°C)	Pressure (bar)
Turbine	259.70	7.3
Recuperator (Hot Stream)	222.62	0.152
Condenser	120.20	0.112
Pump	80.49	0.102
Recuperator (Cold Stream)	80.92	8.1
Pre-heater	172.12	7.6
Evaporator	249.00	7.5
Pipe	259.70	7.4

Temperature and pressure for each stream are inserted into Excel sheet and these values are utilized by Visual Basic program for calculation of enthalpy for this MDM stream. Pressure vs. enthalpy graph was plotted by using enthalpy, temperature and pressure of MDM in Excel. This graph for point 7 is shown in Figure 4.4. P vs. h graphs for other points are demonstrated in Appendix A4.

4. RESULTS AND DISCUSSION

Power generation of seventh data group is calculated by using this program with these variables and parameters. During the solution of the system, the progress is reported in a window by PSE.

Firstly, the program makes the system analysis. Unless errors are determined about system, the numerical phase is started. After solution process, the results are automatically displayed on the flowsheet. The flowsheet and results of point 7 are shown in Figure 4.1. Moreover, Appendix A.3 shows the flowsheet for each point.

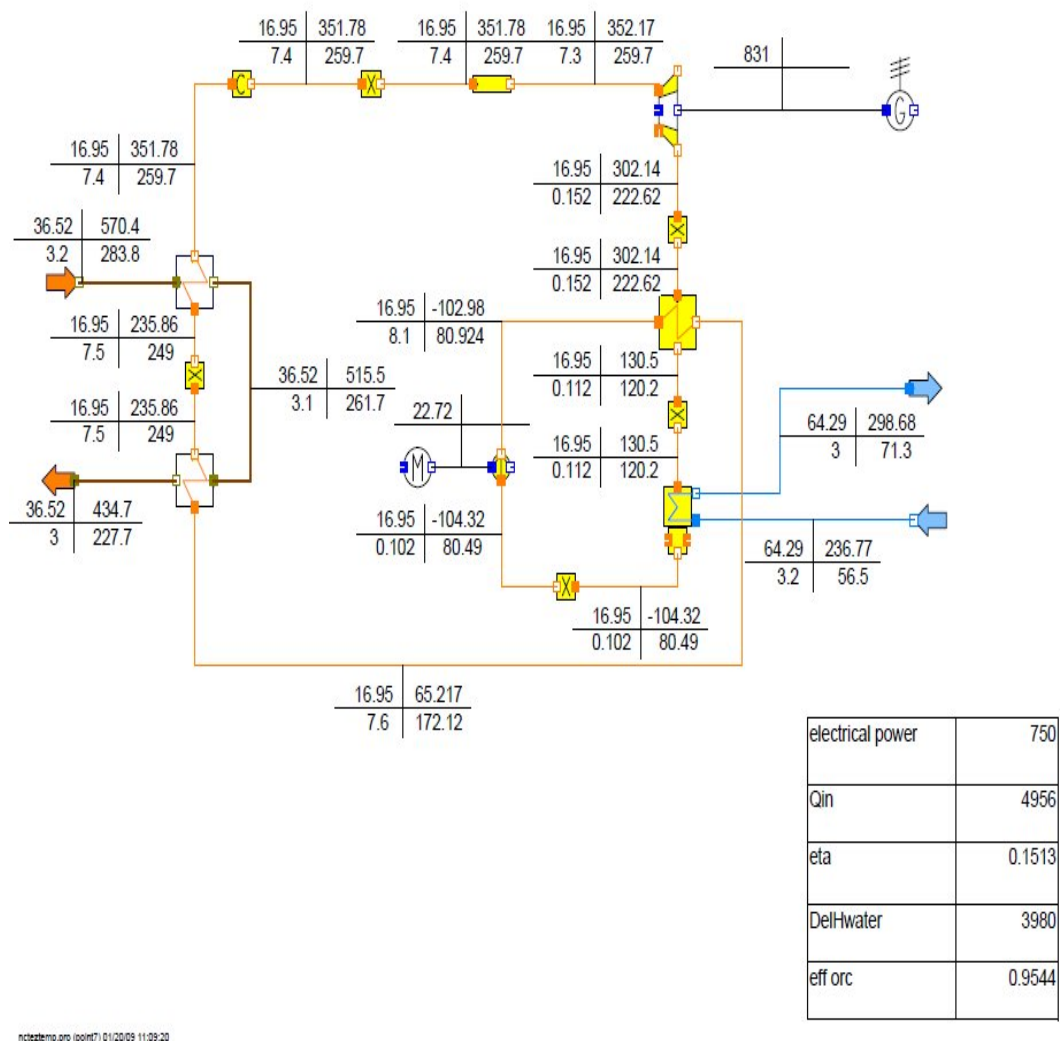


Figure 4.1: Flowsheet of ORC module in IPSEpro

Electrical power, input energy of ORC, electrical efficiency, enthalpy changes of water, overall efficiency of ORC, which are calculated, are shown by using data frames in the flowsheet. Data frames are user - defined table that display additional project information [38]. These values that are showed into data frame can be easily moved to Excel sheet. These values for all points are tabulated in Table 4.1.

Table 4.1: Calculated values by IPSEpro

Point	Input Energy	Electrical Efficiency	Enthalpy Differences of Water	Overall Efficiency	Electrical Power (Calculated)
1	5106.338	0.1521	4095.845	0.9542	777
2	4956.308	0.1505	3985.267	0.9546	746
3	4979.723	0.1507	4003.319	0.9546	750
4	4864.43	0.1514	3906.369	0.9544	736
5	4824.07	0.1524	3867.688	0.9542	735
6	4830.909	0.151	3881.109	0.9544	729
7	4956.437	0.1513	3980.318	0.9544	750
8	4256.401	0.1514	3414.461	0.9536	645
9	4141.016	0.1508	3324.168	0.9535	624
10	4356.439	0.1506	3499.764	0.9539	656
11	4270.299	0.1501	3431.964	0.9538	641
12	4479.994	0.1524	3588.417	0.9534	683
13	4316.056	0.1501	3468.604	0.9537	648
14	4330.982	0.1511	3476.135	0.9537	654
15	3570.771	0.1481	2875.732	0.9535	529
16	3344.785	0.145	2706.299	0.9541	485
17	3551.642	0.1483	2859.702	0.9535	527
18	3576.681	0.1473	2884.717	0.9538	527
19	3591.771	0.1498	2885.839	0.9532	538
20	3493.578	0.1497	2807.226	0.9533	523
21	3539.864	0.148	2851.602	0.9536	524
22	4710.521	0.1513	3780.706	0.9539	713
23	4611.784	0.1514	3699.399	0.9535	698
24	4583.906	0.151	3678.786	0.9536	692
25	4378.388	0.149	3524.623	0.954	652
26	4571.693	0.1476	3688.024	0.9543	675
27	4866.391	0.15	3915.506	0.9546	730
28	4645.891	0.1503	3733.54	0.9539	698

Error between measured and calculated power generation that is tabulated in Table 4.2 was calculated by using Equation 4.1. The deviation for point 7 was determined as 1.57%. The largest deviation from among all data groups was computed as 6.30% that belong to point 23. Point 3 has the lowest deviation as 0.08%.

$$\varepsilon = \frac{(P_{measured} - P_{calculated})}{P_{measured}} * 100 \quad (4.1)$$

Table 4.2: Deviation of calculated and measured power generation

Point	Deviation (%)	Point	Deviation (%)	Point	Deviation (%)	Point	Deviation (%)
1	2.31	8	0.98	15	-5.57	22	0.88
2	-1.89	9	2.44	16	-1.24	23	6.30
3	0.08	10	0.91	17	-0.16	24	0.10
4	3.99	11	-2.88	18	-2.11	25	2.04
5	5.73	12	0.45	19	-1.89	26	-4.45
6	2.34	13	-1.06	20	2.42	27	2.40
7	1.57	14	-0.49	21	-1.74	28	0.67

These deviations are not large and are acceptable for simulation program. Some graphs were plotted for research of deviation reasons and deviation analysis. These graphs are related variables of turbine because it is considered that calculated power generation and deviations are mostly affected by these variables.

Influence of calculation power generations (load of generator) to deviations is analyzed with first graph. These two values are not proportional to each as showing in Figure 4.2. Therefore, trendline was plotted for observation of tendency. According to trendline of this graph, deviation passes from negative value to positive with increasing load.

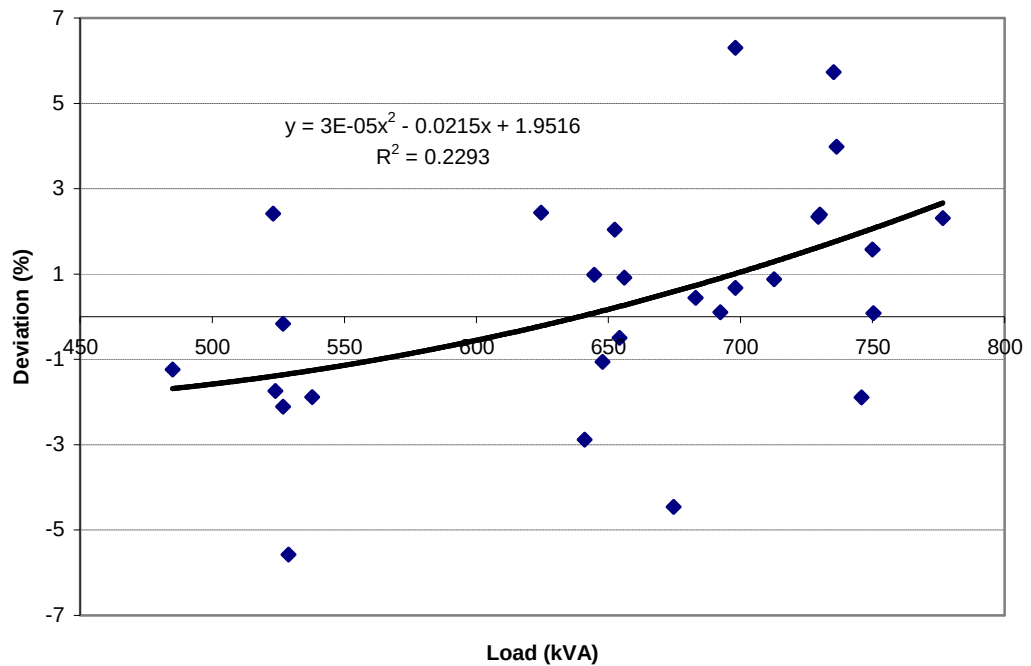


Figure 4.2: The Graph of load of generator (kVA) vs. deviation (%)

For second graph was plotted for investigation of relation between enthalpy differences of MDM in turbine and calculated or measured power generation. Also trendlines were added in this graph that is shown in Figure 4.3. According to this graph, the deviation is goes from negative to positive values like the first graph.

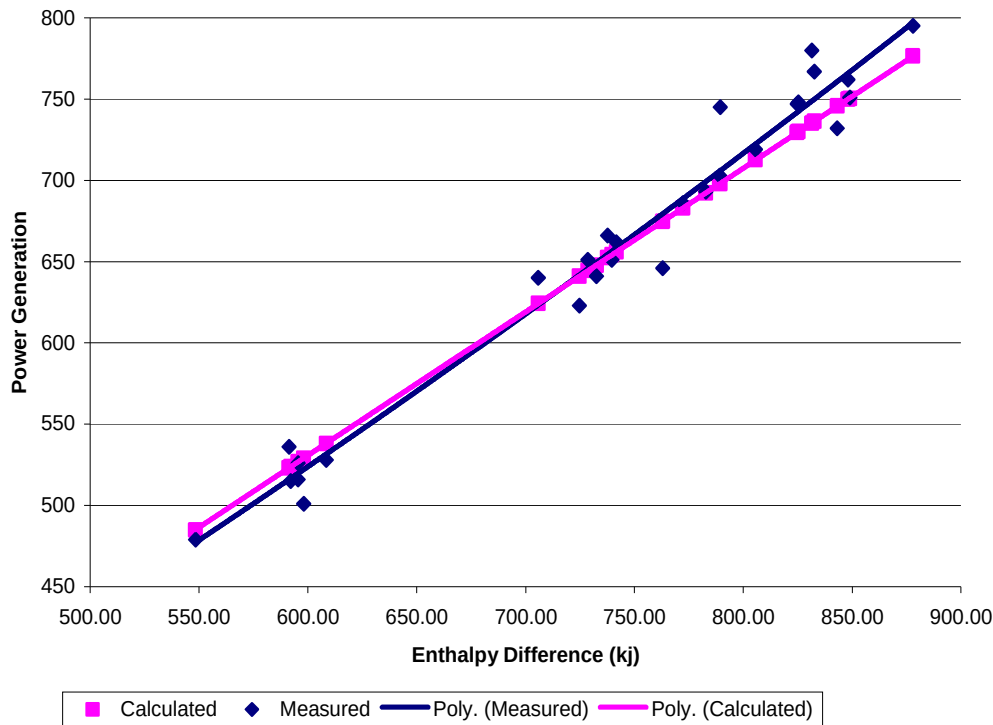


Figure 4.3: The graph of enthalpy differences in turbine (kJ) vs. calculated and measured power generation (kVA)

Two graphs were prepared for making deviation analysis and investigation of relation between variables of turbine and calculated or measured power generation and deviations. It is considered that these values are mostly affected by variables of turbine. These plots are related to deviations vs. calculation power generations (load of generator), enthalpy differences of turbine vs. calculated and measured power generation.

These variables of turbine are not proportional to deviations and both of power generations. Consequently, trendline was plotted for observation of tendency. According to trendline, deviation of calculated and measured power generation goes from negative side to positive. Magnitude of deviation converges to zero until a point that has power generation as about 650 kVA of each graph and than this starts to extend with increase power generation.

The reasons of these deviations cannot be a perfect fit, because each point that is studied in this program has more than one variable. Moreover, the rest of deviations are oscillation differences and inaccuracy of sensors.

By using enthalpy vs. pressure graph of ORC module, enthalpy change of this cycle and phase change of MDM are observed. This graph for point 7 is shown in Figure 4.4. According to graph, MDM is superheated vapor at inlet stream of turbine where enthalpy of MDM decreases with decrease temperature and pressure. Released energy is converted to mechanical energy (1-2). After some amount of heat of MDM is transfer to cold stream of MDM in recuperator, MDM converges to saturated liquid (2-3). Enthalpy difference in condenser originates phase change of MDM and MDM is saturated liquid while it enters to pump (3-4). MDM is pump to recuperator as compressed liquid and in the pump during pressure increase sharply, temperature is nearly constant so enthalpy is practically no change (4-5). Liquid MDM which comes to recuperator again, is heated in this equipment but it is still compressed liquid (5-6). Before the evaporator, temperature of MDM rises and this liquid transform saturated liquid in the pre-heater (6-7). This saturated MDM transform to superheated vapor in evaporator and than it pass through pipe where temperature is constant and pressure drop is 0.1 bar. Therefore, change of MDM properties in the pipe is not prominent in graph. Finally, MDM enters turbine as superheated vapor. As seen in the graph, simulation made by IPSE pro is not in contradiction with practical application of ORC.

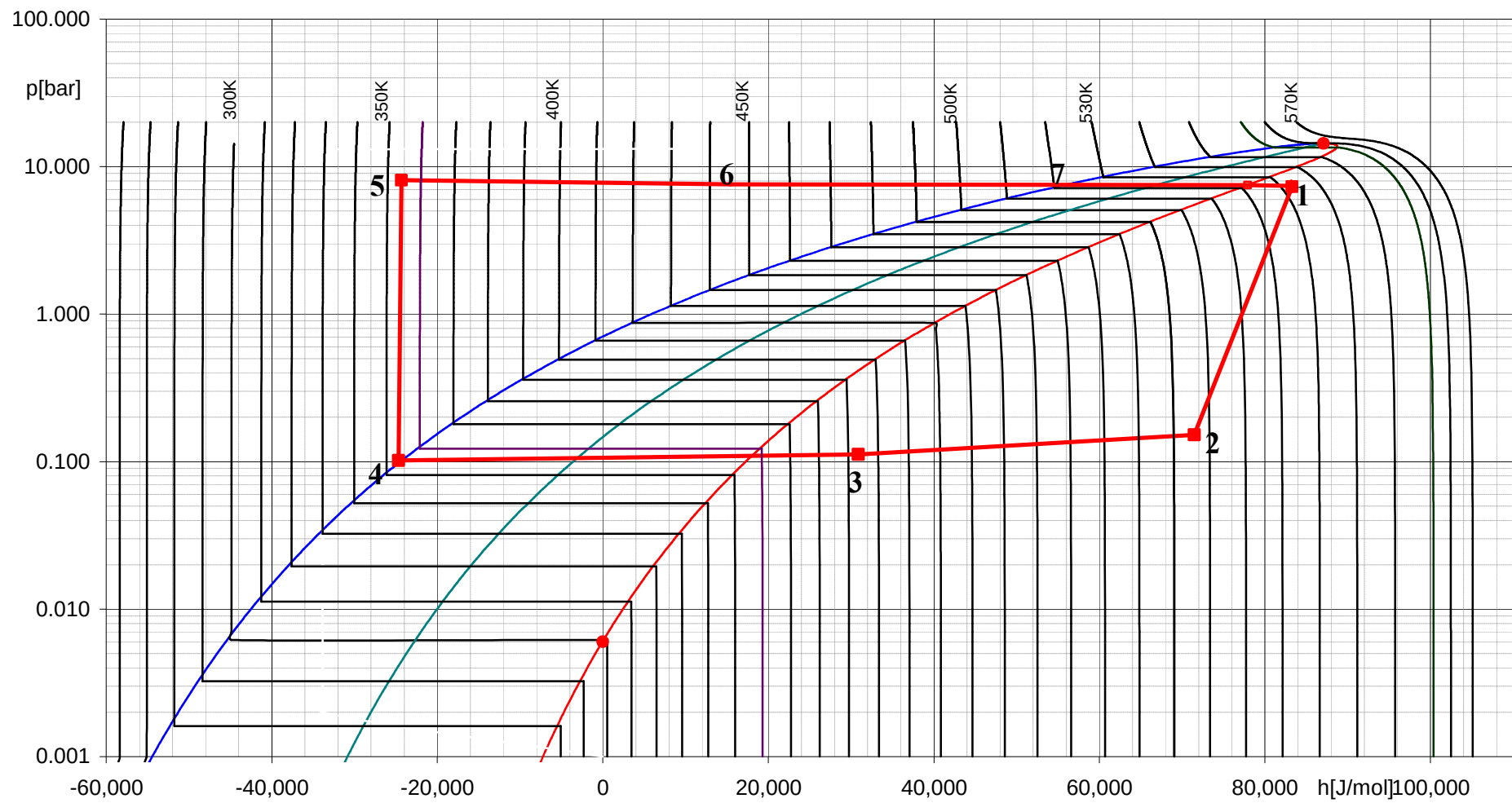


Figure 4.4: P vs. h graph of ORC for point 7

5. CONCLUSION AND RECOMMENDATIONS

Renewable energy resources have been attracted researchers due to the limitation of energy reserve and environmental problems in recent years. Biomass is one of these renewable energy resources is an environmentally strategic energy resource, which can be produced everywhere and it has also influence on socio-economic development. Biomass fired plants have been operated and built in all over the world. Generally, these plants simultaneously produce bioelectricity and bioheat by using CHP technology. CHP plant has higher efficiency power generation compared to conventional electricity generation since it also uses residual heat for useful energy generation.

In small or medium biomass fired CHP plant, ORC module can be utilized for electricity and heat production. Electricity can be produced at lower temperature and pressure with usage of organic liquid in ORC module.

A good example of small scale biomass fired CHP plant is plant in Scharnhauser Park in Stuttgart, Germany. Natural wood scraps and forested wood are combusted in this plant and combusted energy are utilized by ORC module to cover 80% of the heating and approximately 50% of the electrical power of energy demand of this area.

A simulator is a collection of hardware and software systems, which are utilized to imitate the behaviors of system or phenomenon. Sustainability and efficiency of the system can be assigned by using simulation. Moreover, simulation programs help to give some important decision about the system so that efficiency can be gone up with decrease operation costs. Because of these reasons, simulator is important for energy engineering and power plant.

In this study, a simulation program of ORC in Scharnhauser Park CHP plant was developed with IPSEpro that is software module for process simulation related to energy and chemical engineering. It uses Newton based gradient solver to calculate steady state solution. Twenty eight data groups, which were taken from this plant, were utilized in simulation of this ORC for making deviation analysis by comparison

of calculated and measured power generation and controlling of suitability IPSEpro with ORC module of CHP plant in Scharnhauser Park.

Initially, this program calculates electrical power generation, input energy of ORC, electrical efficiency, enthalpy changes of water, overall efficiency of ORC. Then, deviation between measured and calculated power generation is calculated. Deviations shows that the program simulates the real power generation with acceptable error, with the highest error of 6.30%.

Variables of turbine were selected for deviation analysis since they influence power generation. However, these variables of turbine are not proportional to deviations and both of power generations so a trendline was plotted for observation of tendency. According to tendencies, magnitude of deviation converges to zero until a point of each graph and then this starts to extend with increased power generation and enthalpy difference.

Each point that is studied in the simulation program owns more than one variable so that exact reason or influence parameters of these deviations cannot be determined. Moreover, the rest of deviations may come from oscillation differences and/or inaccuracy of sensors.

Also, enthalpy vs. pressure graph of ORC module in Scharnhauser Park CHP plant are plotted by using temperature and pressure of each MDM stream that are set values of IPSEpro or calculated by this simulation program. Excel sheet based on Visual Basic is utilized in this study. The aim of plotting of these graphs is to observe enthalpy change of this cycle and phase change of MDM. According to this study, phase and enthalpy changes in simulation program made by IPSEpro are not in contradiction with ORC module in real application.

In a conclusion, suitability IPSEpro simulation program with ORC module in Scharnhauser Park CHP plant is investigated in this study. Deviation of power generation, phase and enthalpy changes are observed. According to these analysis, simulation of ORC module made by IPSEpro imitates to real ORC module and is convenient and usable for ORC module in Scharnhauser Park CHP plant.

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APPENDICES

APPENDIX A1: Pollutants from biomass combustion

APPENDIX A2: Employed variables of IPSEpro simulation program

APPENDIX A3: IPSEpro flowsheet for each data groups

APPENDIX A4: P vs. h graphs of ORC for each data groups

APPENDIX A.1

Table A.1 Pollutants from biomass combustion and their impacts on climate, environment and health [3]

Component	Biomass sources	Climate, environmental and health impacts
Carbon dioxide (CO ₂)	Major combustion product from all biomass fuels.	Climate: Direct greenhouse gas. However, CO ₂ emissions from biomass combustion are regarded as being CO ₂ -neutral with respect to the greenhouse gas effect ¹ since biomass is a renewable fuel.
Carbon monoxide (CO)	Incomplete combustion of all biomass fuels.	Climate: Indirect greenhouse gas through O ₃ formation. Health: Reduced oxygen uptake especially influences people with asthma, and embryos. Suffocation in extreme cases.
Methane (CH ₄)	Incomplete combustion of all biomass fuels.	Climate: Direct greenhouse gas. Indirect greenhouse gas through O ₃ formation.
Non Methane Volatile Organic Components (NMVOC)	Incomplete combustion of all biomass fuels.	Climate: Indirect greenhouse gas through O ₃ formation. Health: Negative effect on the human respiratory system.
Polycyclic Aromatic Hydrocarbons (PAH)	Incomplete combustion of all biomass fuels.	Environment: Smog formation. Health: Carcinogenic effects.
Particles	Soot, char and condensed heavy hydrocarbons (tar) from incomplete combustion of all biomass fuels. Fly-ash and salts.	Climate and environment: Reversed greenhouse effect through aerosol formation. Indirect effects of heavy-metal concentrations in deposited particles. Health: Negative effect on the human respiratory system. Carcinogenic effects.
Nitrogen oxides (NO _x (NO, NO ₂))	Minor combustion product from all biomass fuels containing nitrogen. Additional NO _x may be formed from nitrogen in the air under certain conditions.	Climate and environment: Indirect greenhouse gas through O ₃ formation. Reversed greenhouse gas effect through aerosol formation. Acid precipitation. Vegetation damage. Smog formation. Corrosion and material damage. Health: Negative effect on the human respiratory system. NO ₂ is toxic.
Nitrous oxide (N ₂ O)	Minor combustion product from all biomass fuels containing nitrogen.	Climate: Direct greenhouse gas. Health: Indirect effect through O ₃ depletion in the stratosphere. ²

Table A.1: Pollutants from biomass combustion and their impacts on climate, environment and health (Continues) [3]

Component	Biomass sources	Climate, environmental and health impacts
Ammonia (NH ₃)	Small amounts may be emitted as a result of incomplete conversion of NH ₃ , formed from pyrolysis/ gasification, to oxidized nitrogen-containing components. Secondary NO _x reduction measures by NH ₃ injection (SNCR, SCR).	Environment: Acid precipitation. Vegetation damage. Corrosion and material damage. Health: Negative effect on the human respiratory system.
Sulphur oxides (SO _x (SO ₂ , SO ₃))	Minor combustion product from all biomass fuels containing sulphur.	Climate and environment: Reversed greenhouse gas effect through aerosol formation. Acid precipitation. ³ Vegetation damage. Smog formation. Corrosion and material damage. Health: Negative effect on the human respiratory system, asthmatic effect.
Heavy metals	All biomass fuels contain heavy metals to some degree, which will remain in the ash or evaporate.	Health: Accumulate in the food chain. Some are toxic and some have carcinogenic effects.
(Ground level) Ozone (O ₃)	Secondary combustion product formed from atmospheric reactions including CO, CH ₄ , NMVOC and NO _x .	Climate and environment: Direct greenhouse gas. Vegetation damage. Smog formation. Material damage. Health: Indirect effect through O ₃ depletion in the stratosphere. ² Negative effect on the human respiratory system, asthmatic effect.
Hydrogen chloride (HCl)	Minor combustion product from all biomass fuels containing chlorine.	Environment: Acid precipitation. Vegetation damage. Corrosion and material damage. Health: Negative effect on the human respiratory system. Toxic.
Dioxins and furans (PCDD/PCDF)	Small amounts may be emitted as a result of reactions including carbon, chlorine, and oxygen in the presence of catalysts (Cu).	Health: Highly toxic. Liver damage. Central nervous system damage. Reduced immunity defence. Accumulate in the food chain.

APPENDIX A.2

Table A.2: Measured Data of CHP plant in Scharnhauser Park

	Point	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Time	8:46	9:00	9:12	9:24	9:35	9:46	1:00	10:10	10:21	10:33	10:45	10:57	11:09	0:59
Thermaloil	Tfeed(°C)	284	281	283	286	286	283	283.8	275	275	275	272	278	274	274.8
	Treturn(°C)	227	227	228	228	228	228	227.7	223	225	224	224	225	225	224.3
Turbine	Tin(°C)	259.1	258.3	259.7	261	260.9	259.1	259.7	252.1	254.3	253.5	251.6	254.7	253.1	253.2
	Pin(bar)	7.3	7.1	7.3	7.4	7.5	7.2	7.3	6.5	6.6	6.6	6.4	6.8	6.5	6.6
	Tout(°C)	220	220	222	222	221	221	221	214	217	215	215	216	216	215.5
	Pout (mbar)	153	144	151	151	160	151	152	155	177	156	163	168	168	165
Condenser	Tin(°C)	119	120	121	121	120	120	120.2	114	116	116	115	115	116	115.3
	Tout(°C)	76	75	77	76	77	76	76.2	75	78	76	77	78	78	77
	Pout(mbar)	104	92	101	102	102	101	100	97	106	102	104	109	104	104
Pump	Vin (m³/h)	81	77	78	76	77	76	78	70	70	71	71	75	72	72
Water in Condenser	Tin(°C)	57	56	56	56	57	57	56.5	57	58	56	57	57	57	57
	Tout(°C)	72	70	72	71	72	71	71.3	71	75	72	73	74	74	73.2
Recuperator	Tout (°C)	166	166	166	166	166	166	166	162	163	163	163	163	163	162.8
PreHeater	Tout(°C)	248.6	246.1	247.1	248.4	248.7	246.5	247.6	240.9	241.2	241.5	239.4	243.5	240.6	241.2
Generator	Pel(kW)	795	732	751	767	780	747	762	651	640	662	623	686	641	651

Table A.2: Measured Data of CHP plant in Scharnhauser Park (Continues)

	Point	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	Time	11:55	12:08	12:19	12:31	12:42	12:58	1:03	13:43	13:56	14:06	14:19	14:30	14:43	1:00
Thermaloil	Tfeed(°C)	262	261	263	262	264	264	262.7	284	285	282	281	282	286	283.3
	Treturn(°C)	219	219	220	219	220	220	219.5	228	228	227	229	228	228	228
Turbine	Tin(°C)	243.6	243.4	244.2	243.6	244.7	244.5	244	259.5	259.4	257.5	259.3	258.1	259.7	258.9
	Pin(bar)	5.7	5.6	5.7	5.7	5.8	5.8	5.7	7.3	7.4	7.2	7.2	7.2	7.5	7.3
	Tout(°C)	208	209	208	209	208	208	208.3	221	221	220	223	221	222	221.3
	Pout (mbar)	181	191	175	174	175	172	178	188	229	219	219	238	210	217.2
Condenser	Tin(°C)	111	114	111	112	110	110	111.3	120	120	119	122	123	121	120.8
	Tout(°C)	76	77	76	76	75	76	76	81	83	82	83	84	83	82.7
	Pout(mbar)	97	97	92	94	92	95	95	125	137	125	127	139	132	131
Pump	Vin (m³/h)	63	59	62	62	63	61	62	79	82	81	76	81	84	81
Water in Condenser	Tin(°C)	57	56	56	56	56	56	56.2	56	56	56	56	57	57	56.3
	Tout(°C)	73	75	73	74	73	73	73.5	78	80	80	80	81	80	79.8
Recuperator	Tout (°C)	159	159	159	159	159	158	158.8	168	168	168	170	169	169	168.7
PreHeater	Tout(°C)	232.3	231.3	232.9	232.5	233.4	233.4	232.6	247.2	248.7	246.1	246.1	246.3	249	247.2
Generator	Pel(kW)	501	479	527	516	528	536	515	719	745	693	666	646	748	702.8

APPENDIX A3

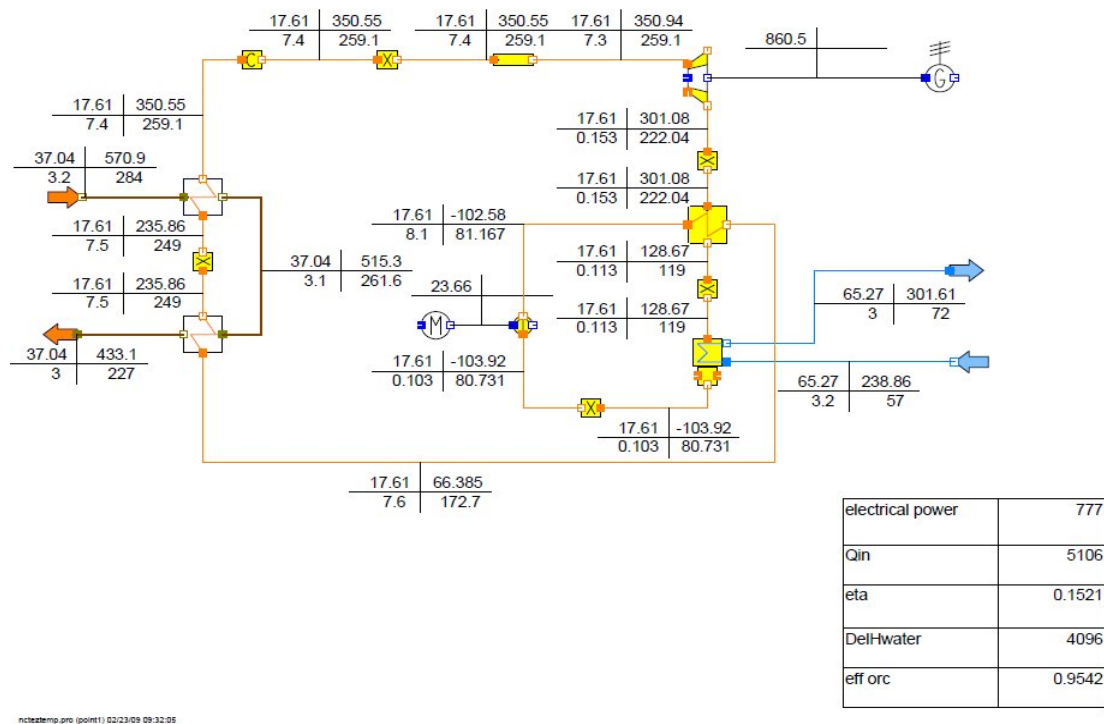


Figure A.3.1: IPSEpro flowsheet for point 1

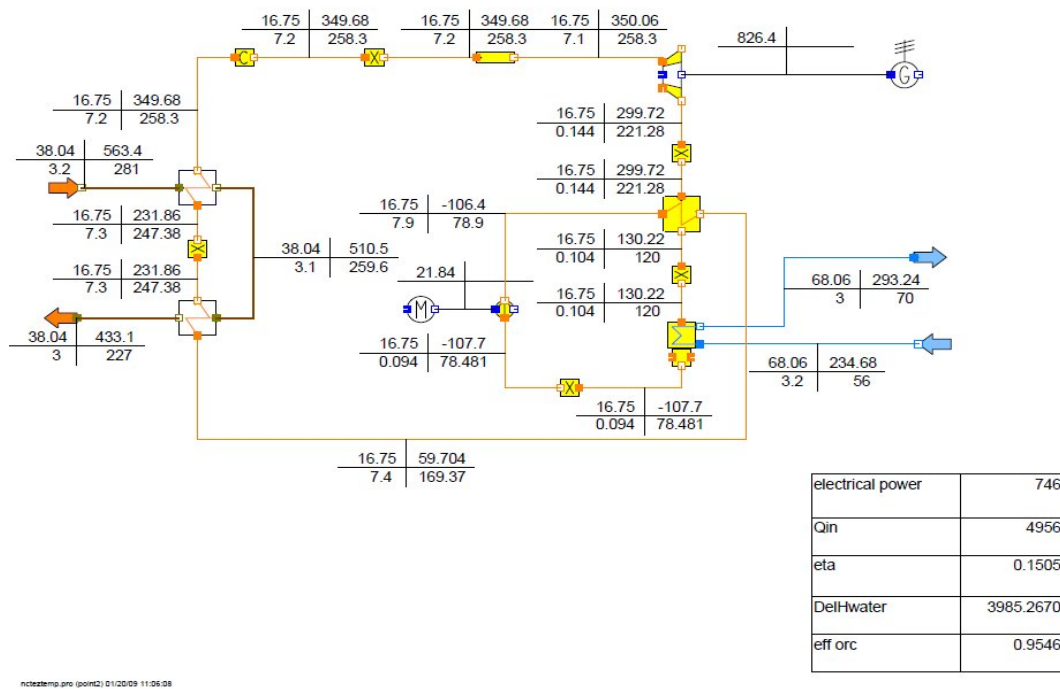


Figure A.3.2: IPSEpro flowsheet for point 2

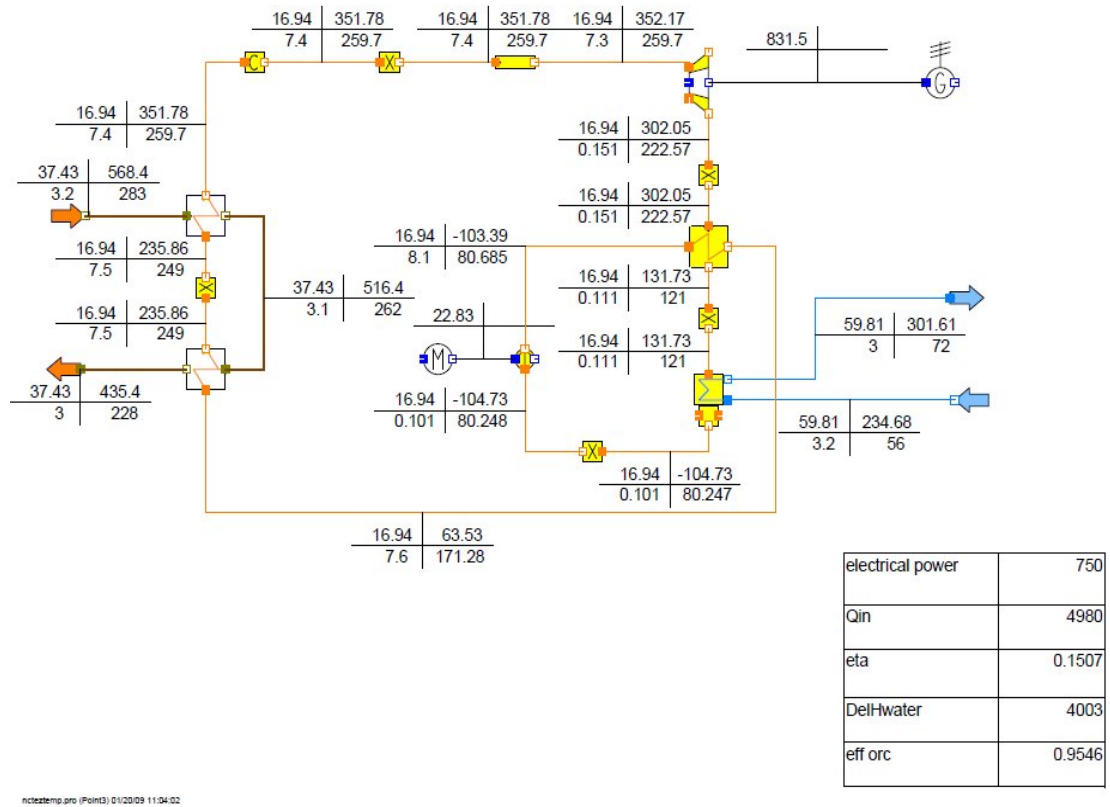


Figure A.3.3: IPSEpro flowsheet for point 3

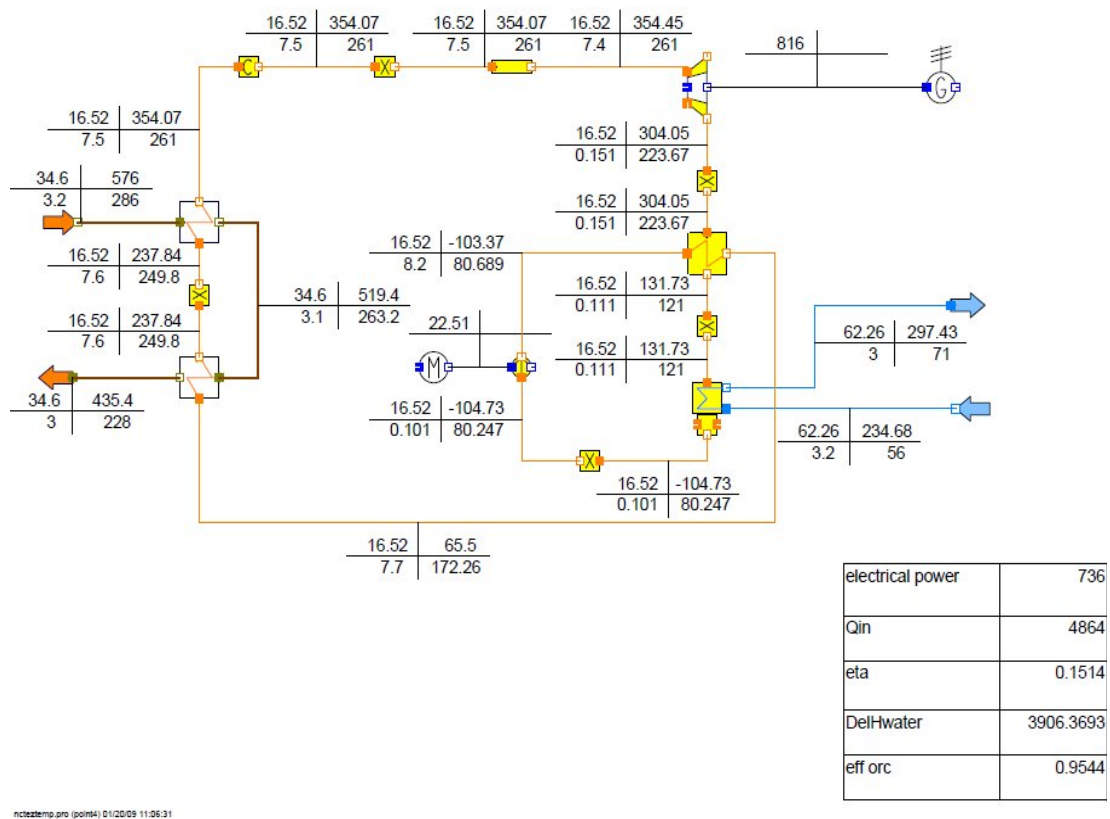


Figure A.3.4: IPSEpro flowsheet for point 4

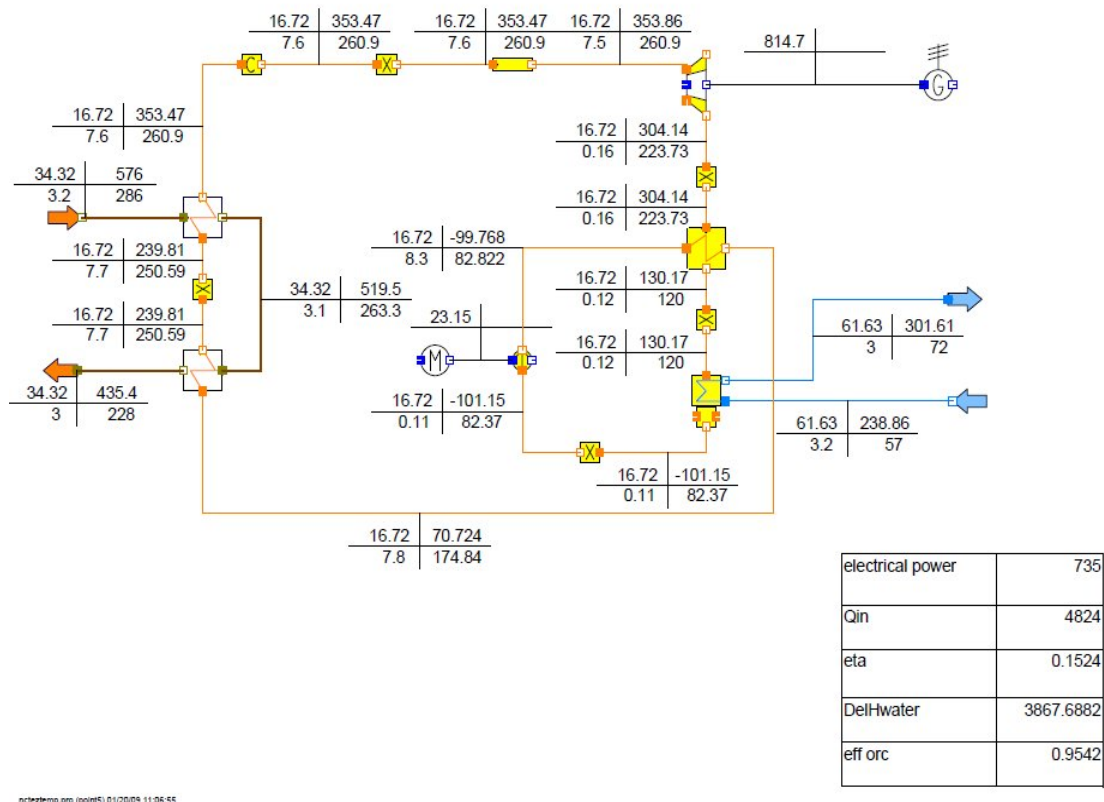


Figure A.3.5: IPSEpro flowsheet for point 5

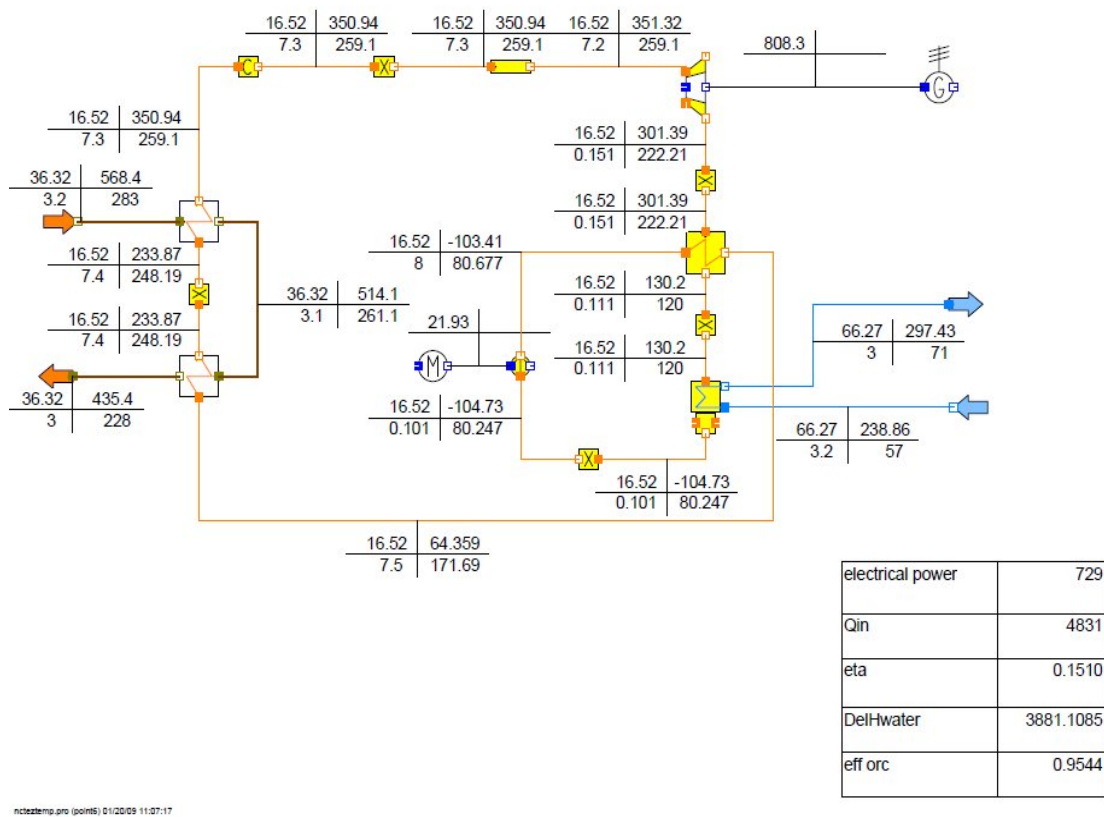


Figure A.3.6: IPSEpro flowsheet for point 6

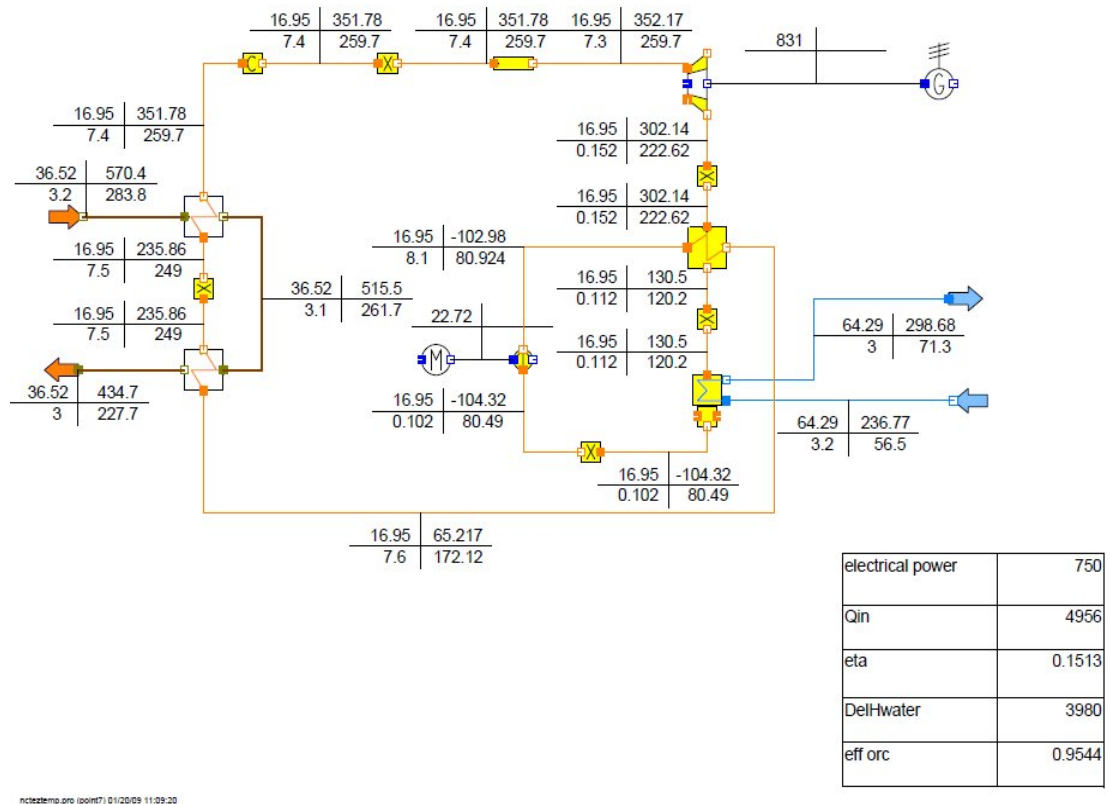


Figure A.3.7: IPSEpro flowsheet for point 7

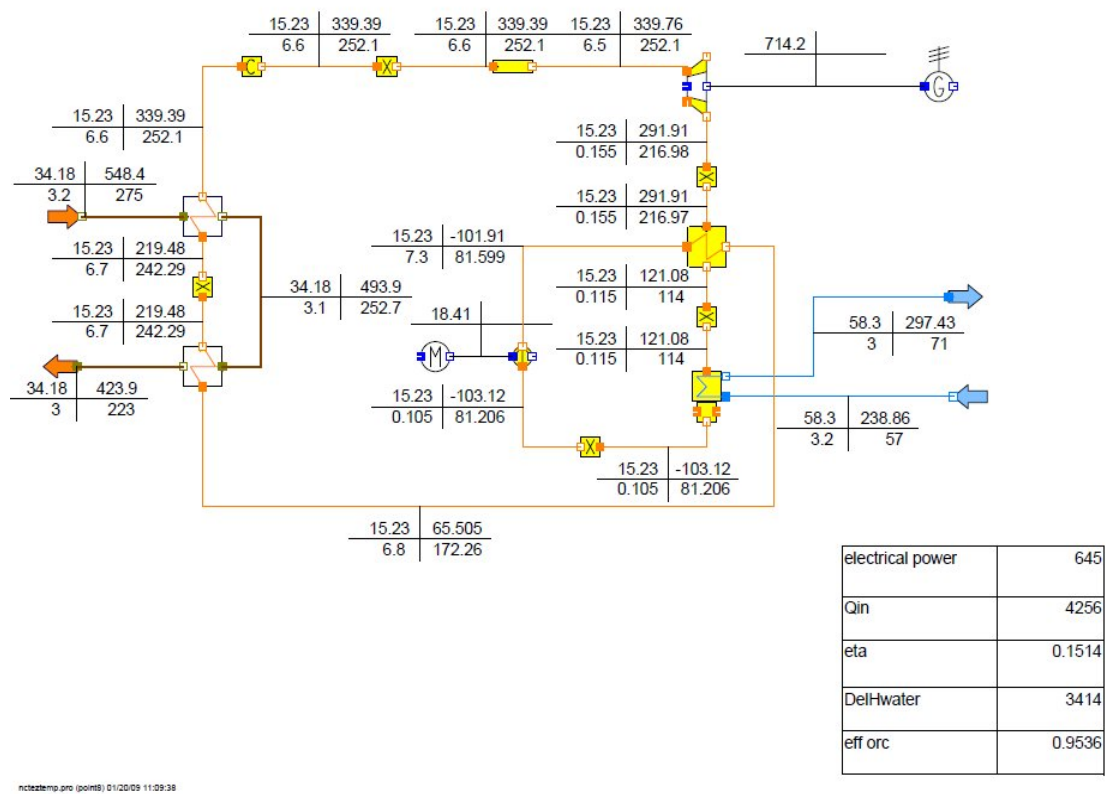


Figure A.3.8: IPSEpro flowsheet for point 8

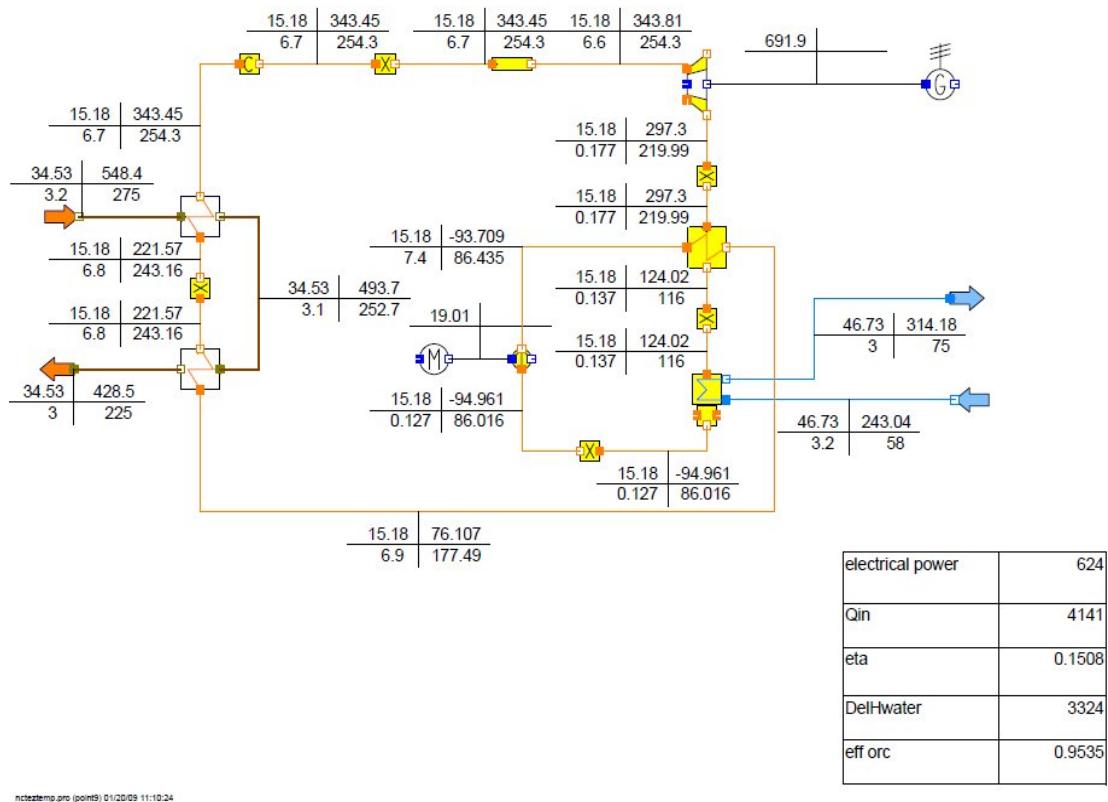


Figure A.3.9: IPSEpro flowsheet for point 9

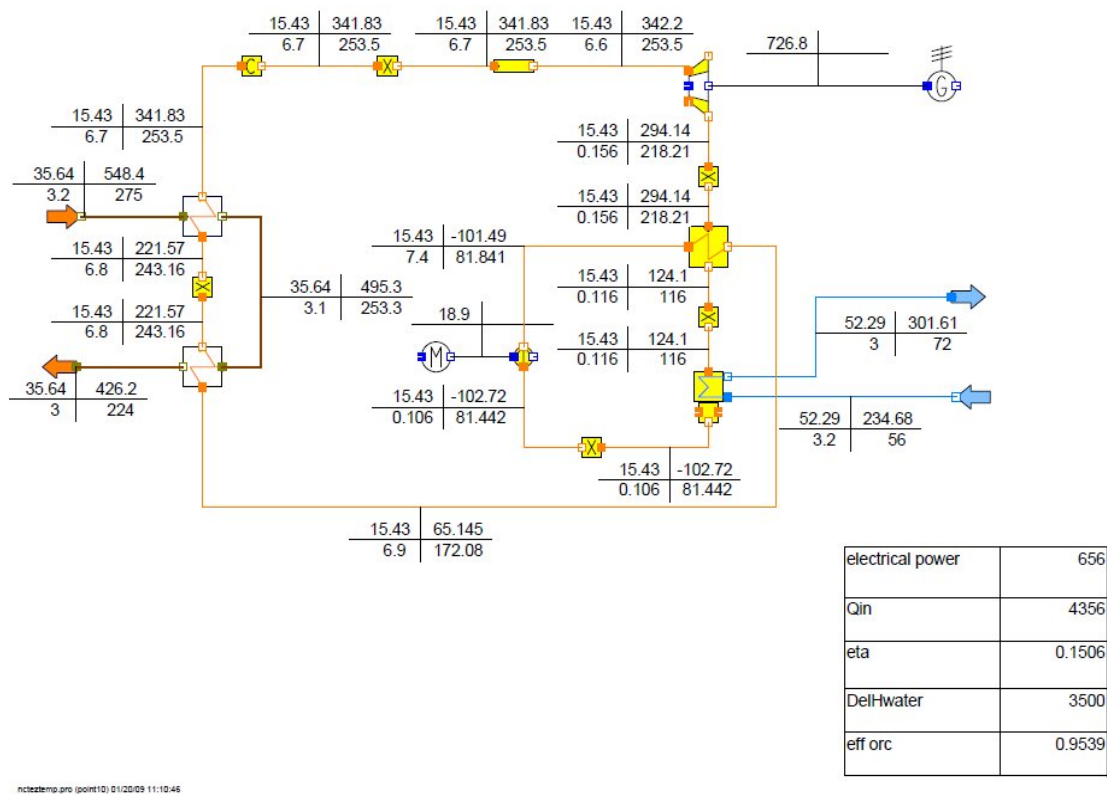


Figure A.3.10: IPSEpro flowsheet for point 10

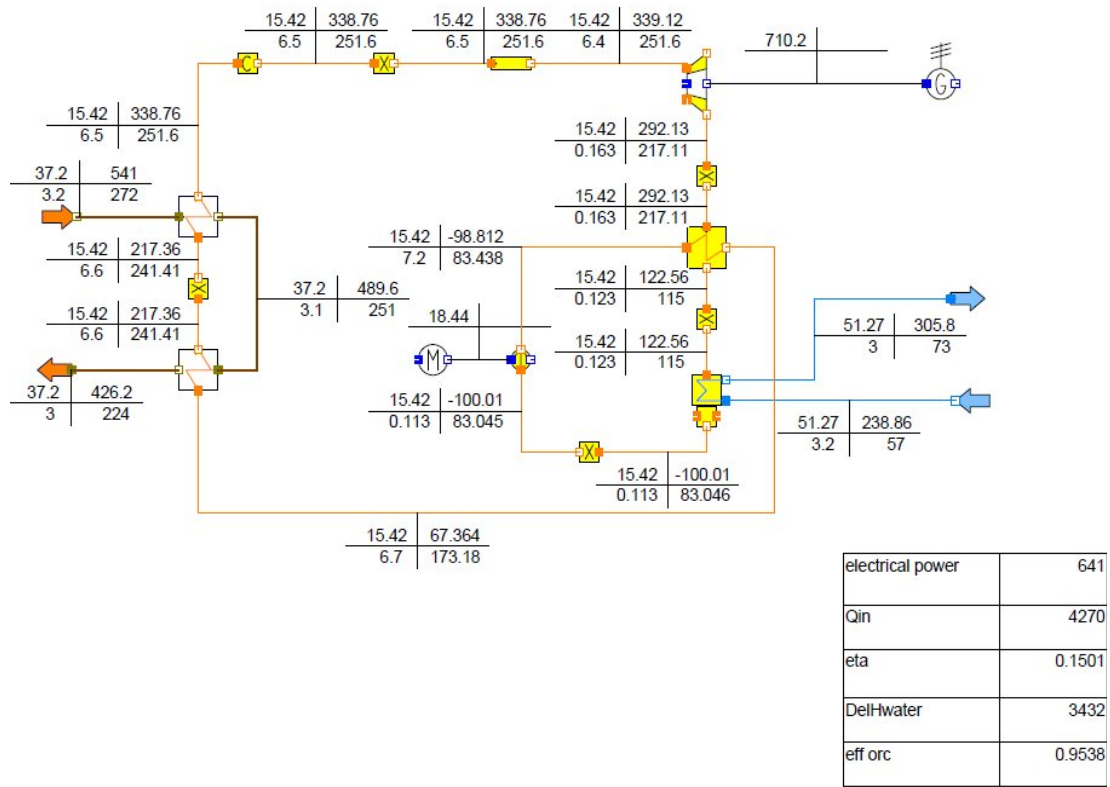


Figure A.3.11: IPSEpro flowsheet for point 11

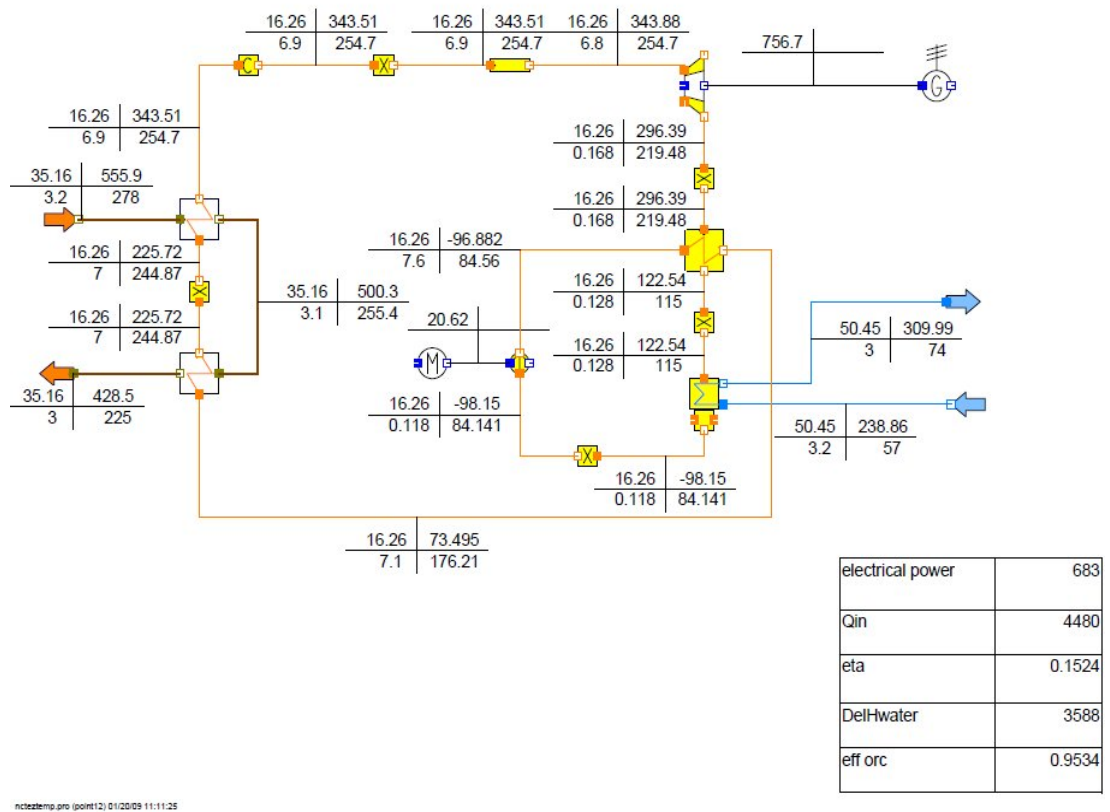


Figure A.3.12: IPSEpro flowsheet for point 12

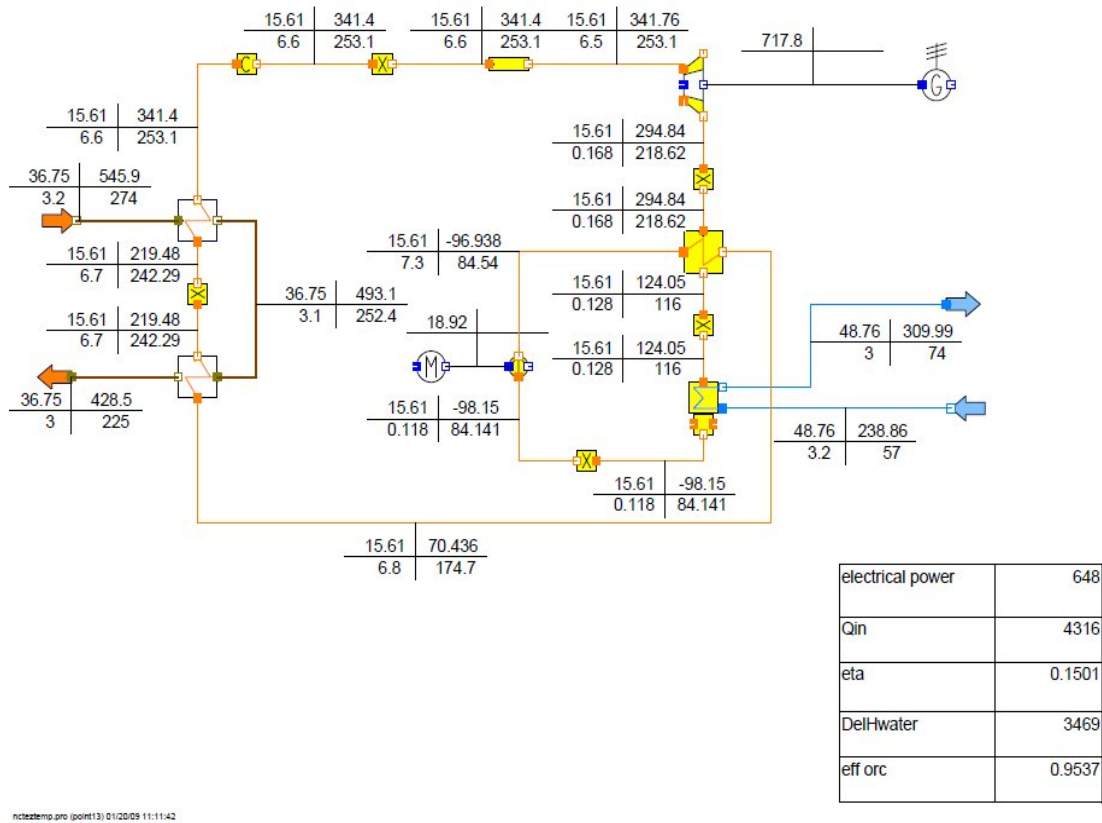


Figure A.3.13: IPSEpro flowsheet for point 13

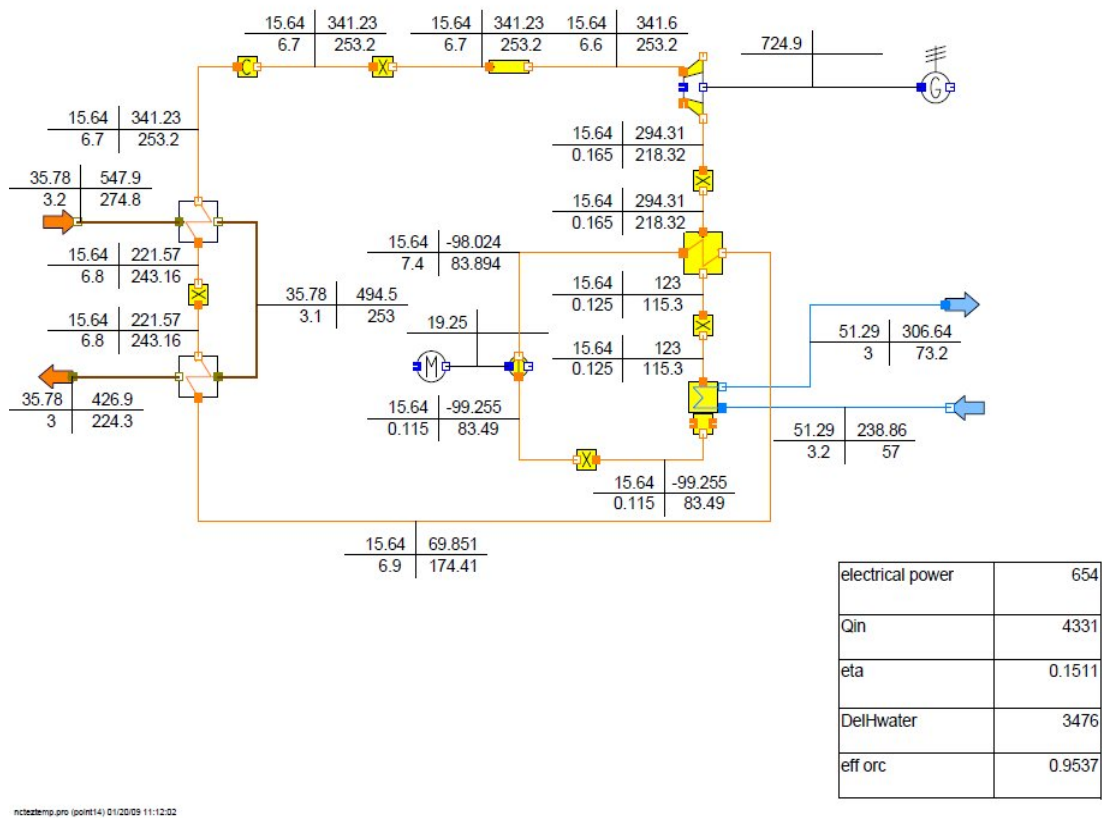


Figure A.3.14: IPSEpro flowsheet for point 14

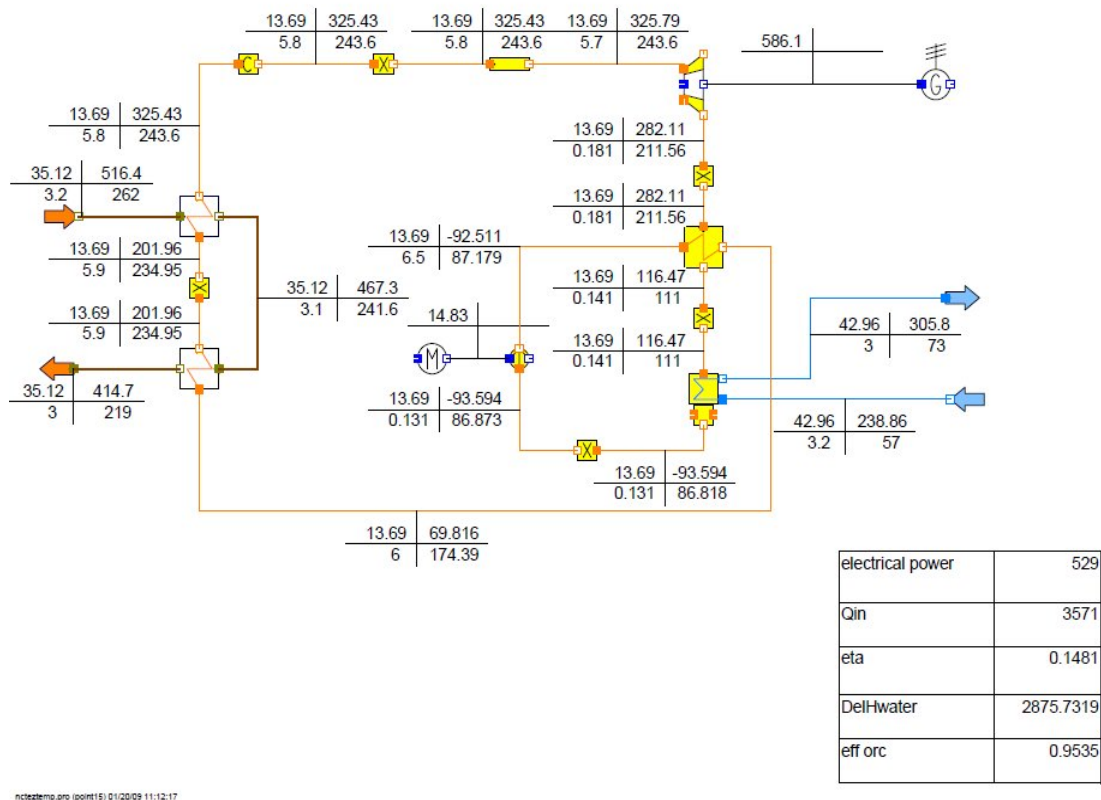


Figure A.3.15: IPSEpro flowsheet for point 15

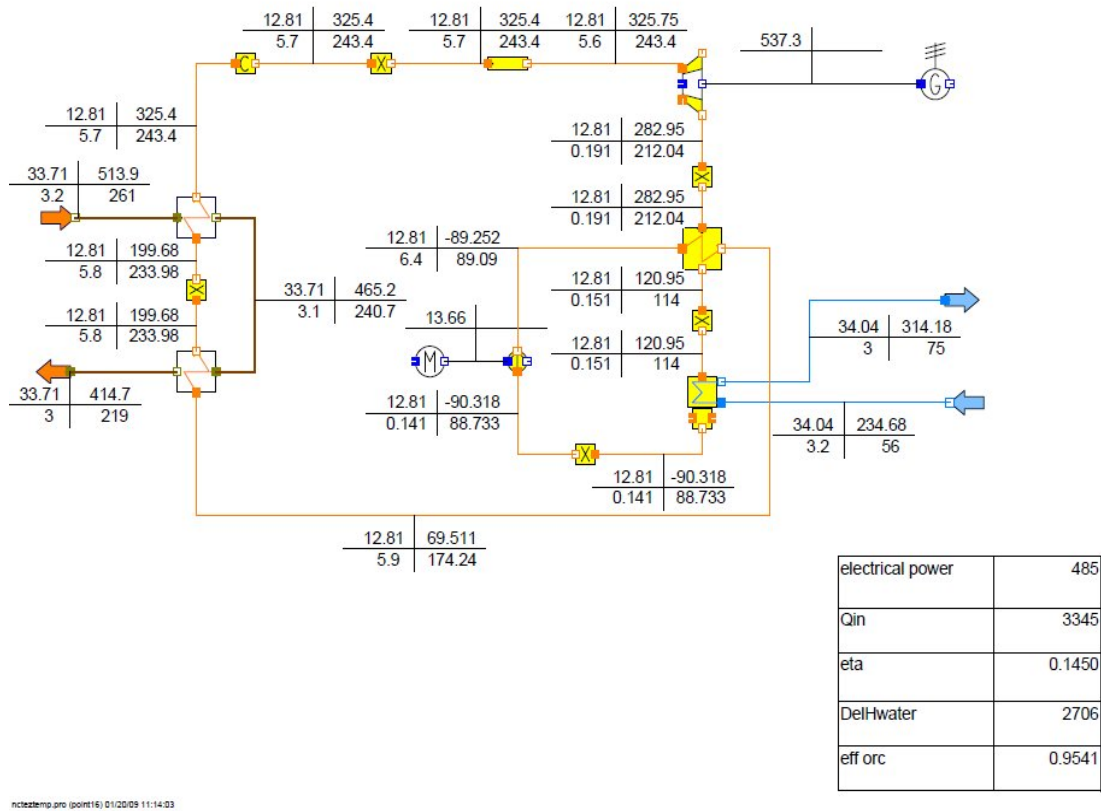


Figure A.3.16: IPSEpro flowsheet for point 16

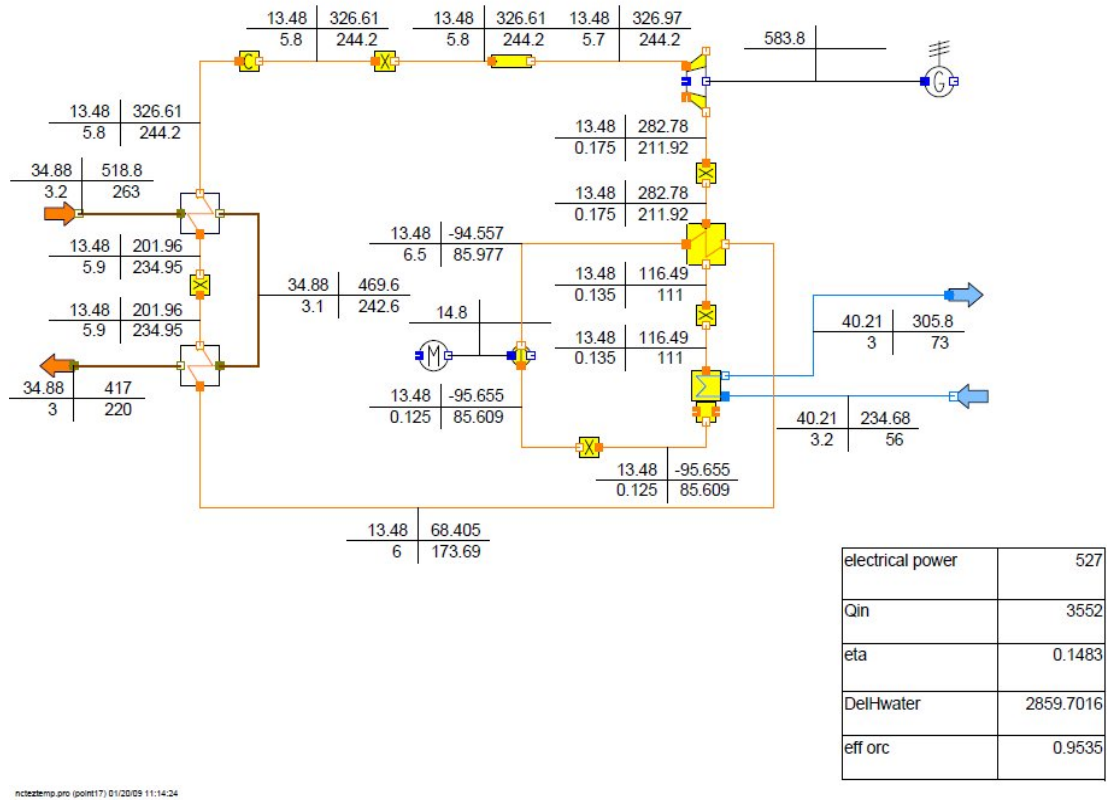


Figure A.3.17: IPSEpro flowsheet for point 17

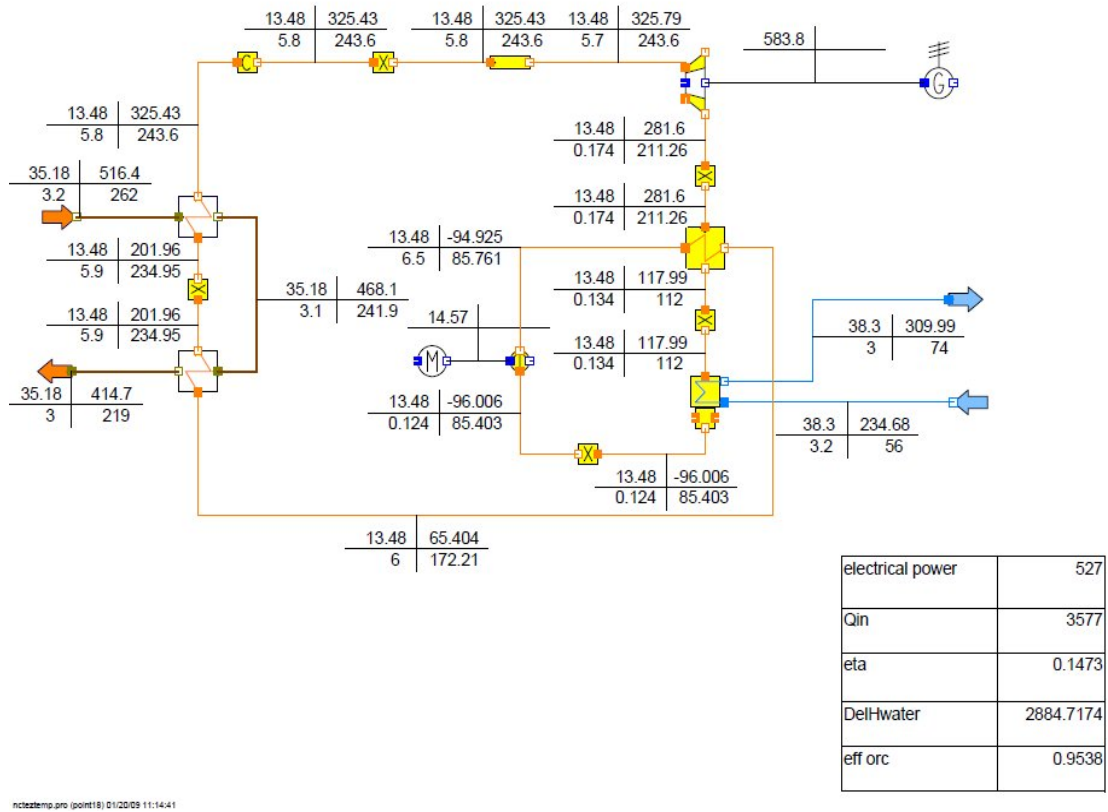


Figure A.3.18: IPSEpro flowsheet for point 18

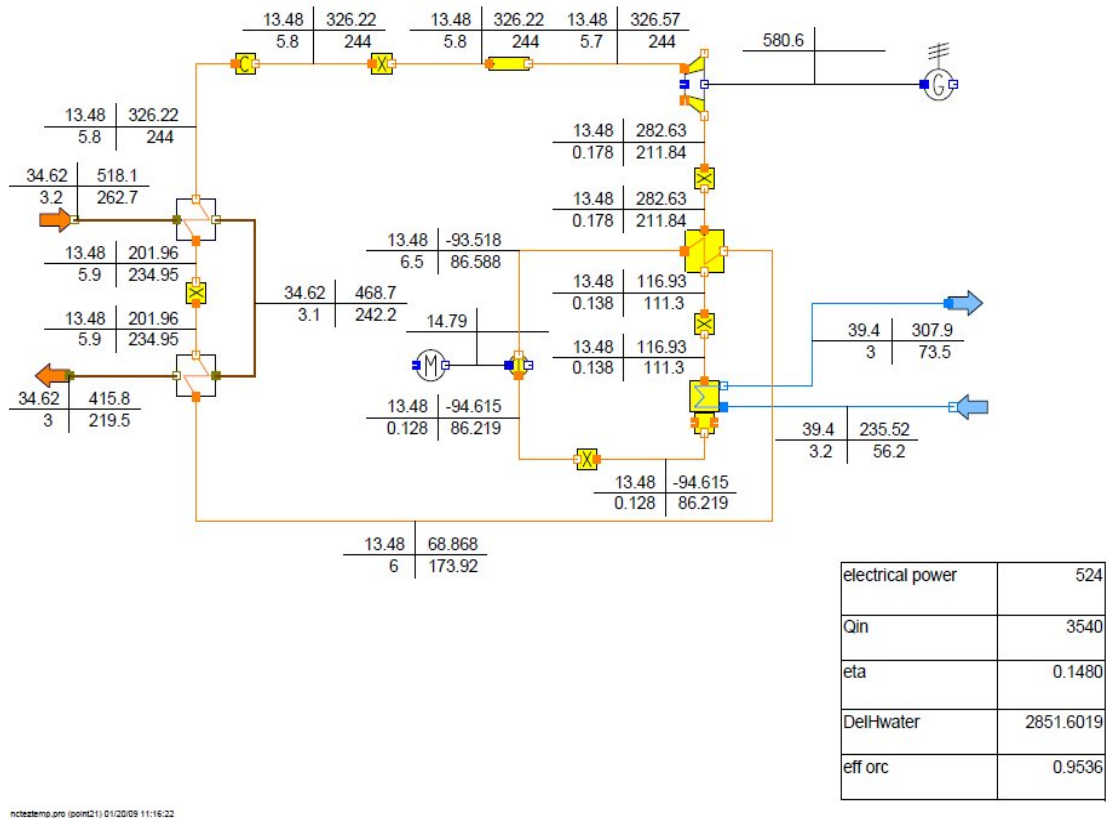


Figure A.3.21: IPSEpro flowsheet for point 21

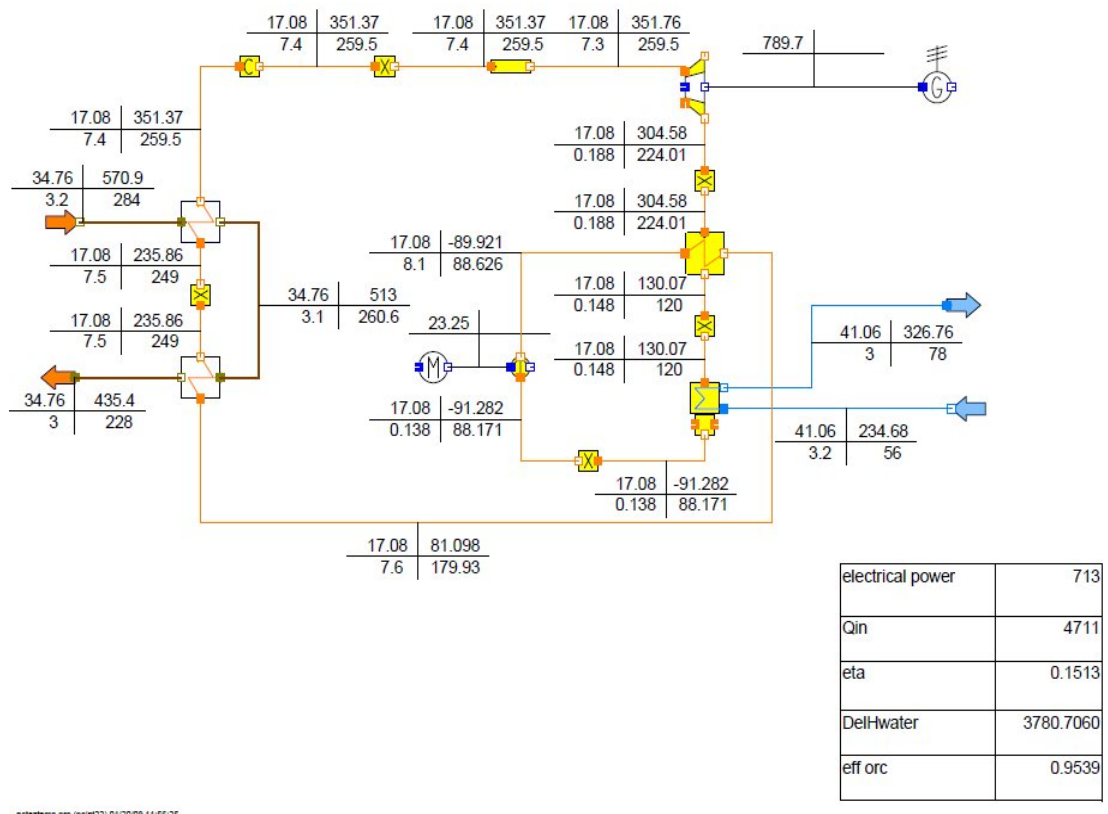


Figure A.3.22: IPSEpro flowsheet for point 22

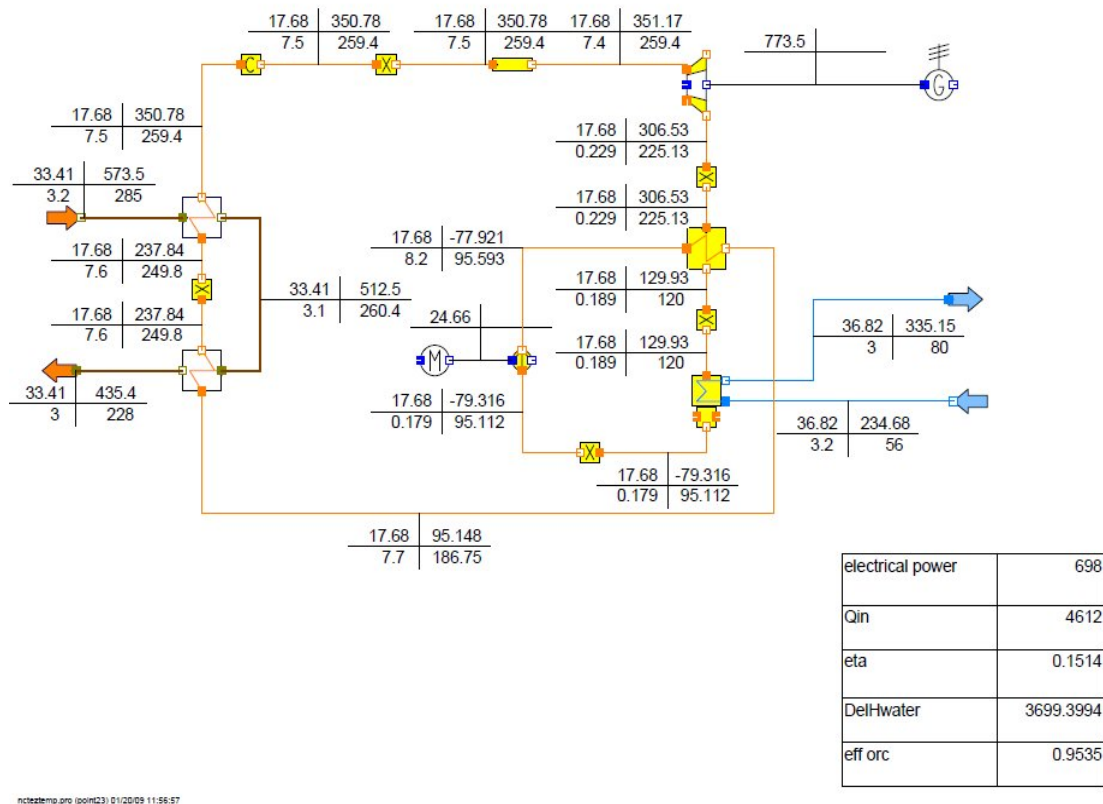


Figure A.3.23: IPSEpro flowsheet for point 23

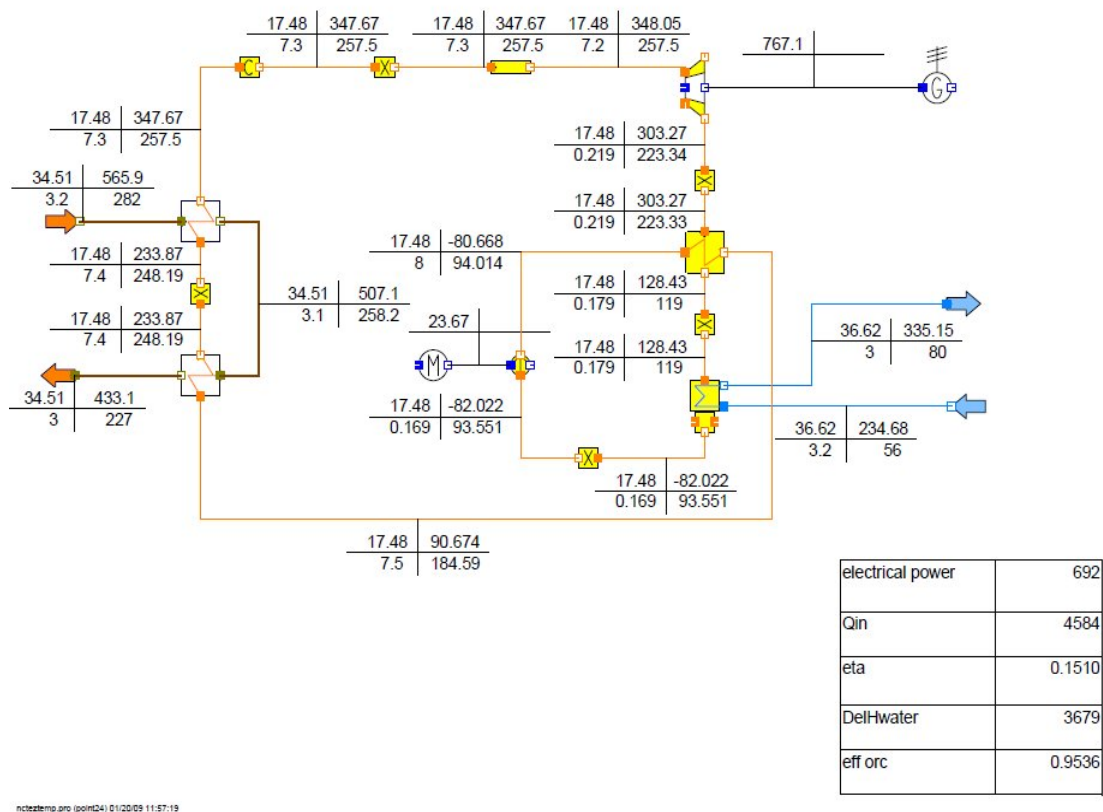


Figure A.3.24: IPSEpro flowsheet for point 24

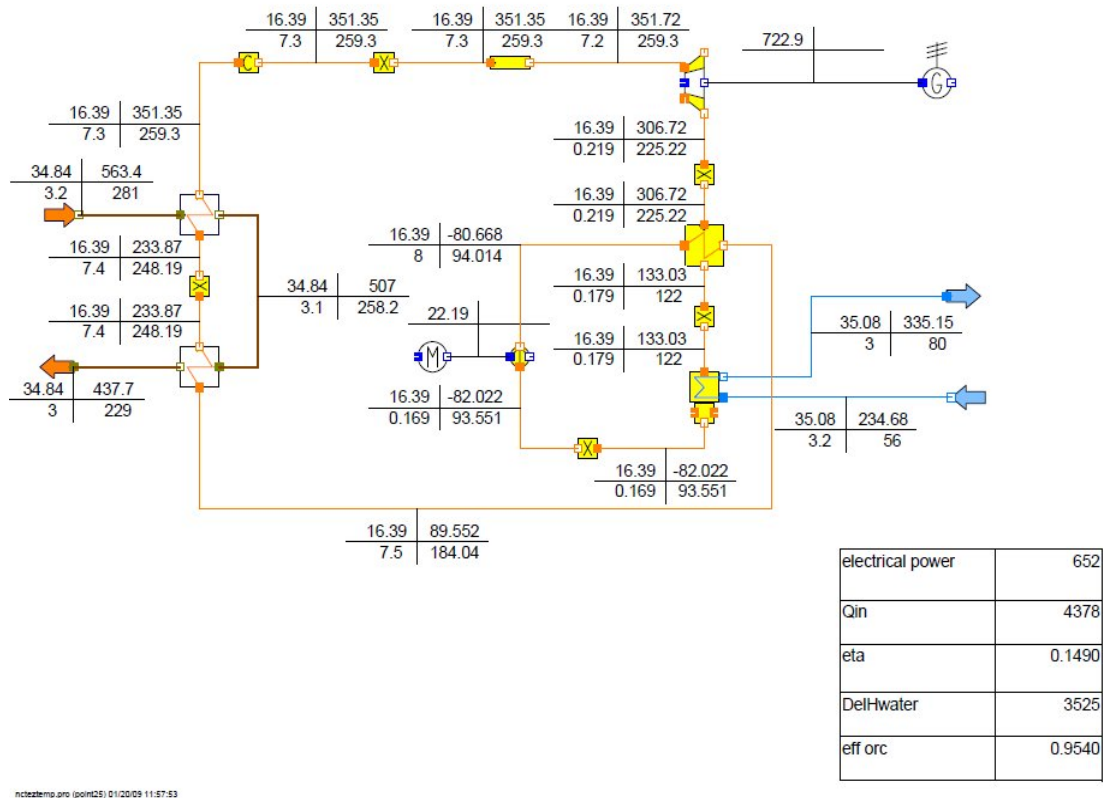


Figure A.3.25: IPSEpro flowsheet for point 25

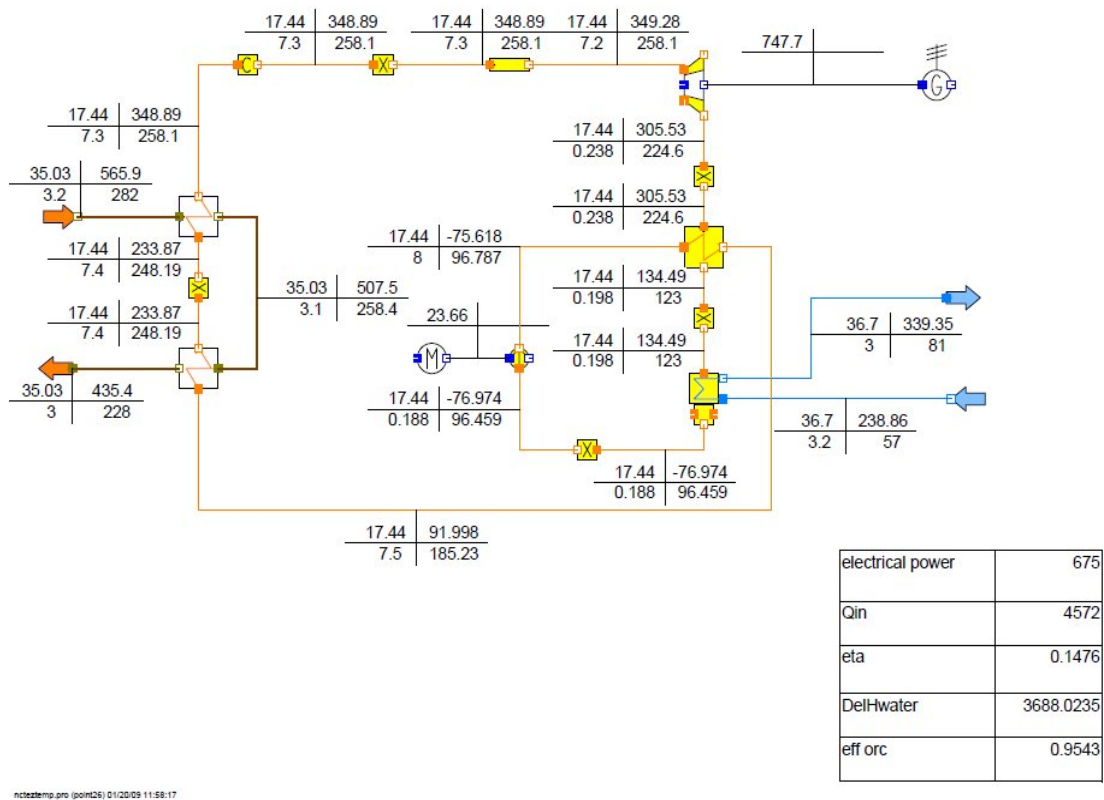


Figure A.3.26: IPSEpro flowsheet for point 26

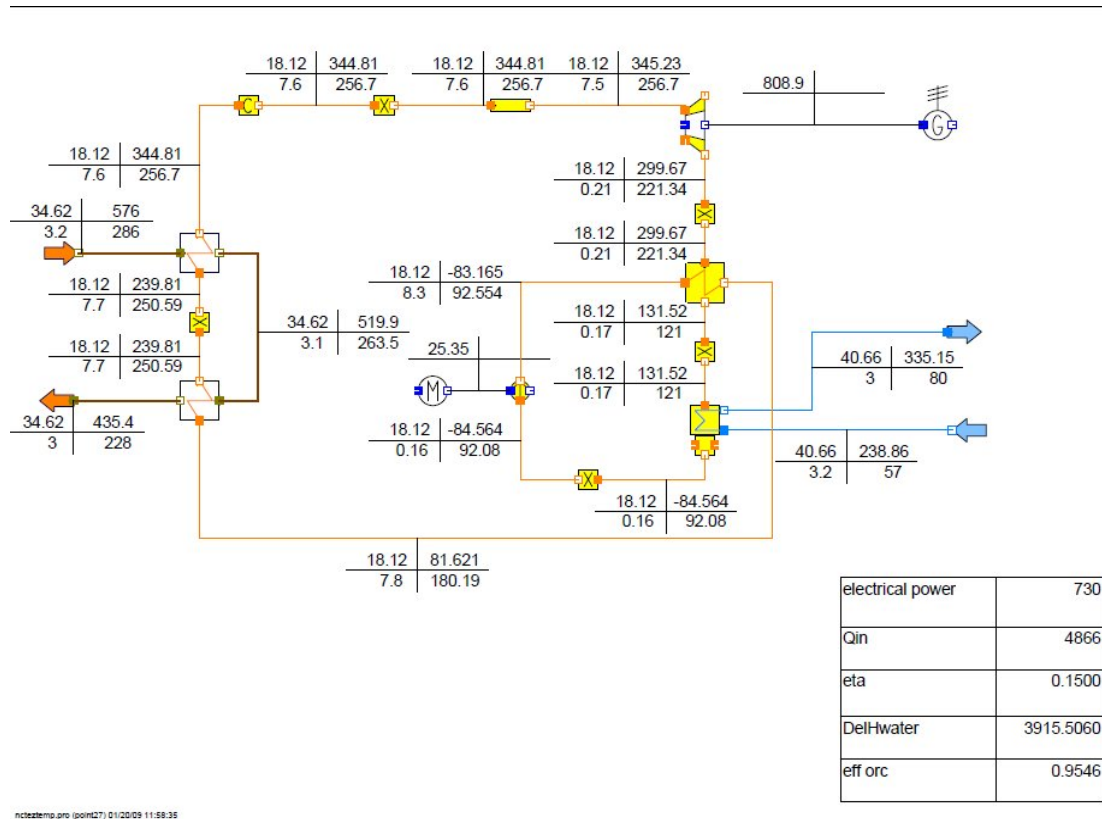


Figure A.3.27: IPSEpro flowsheet for point 27

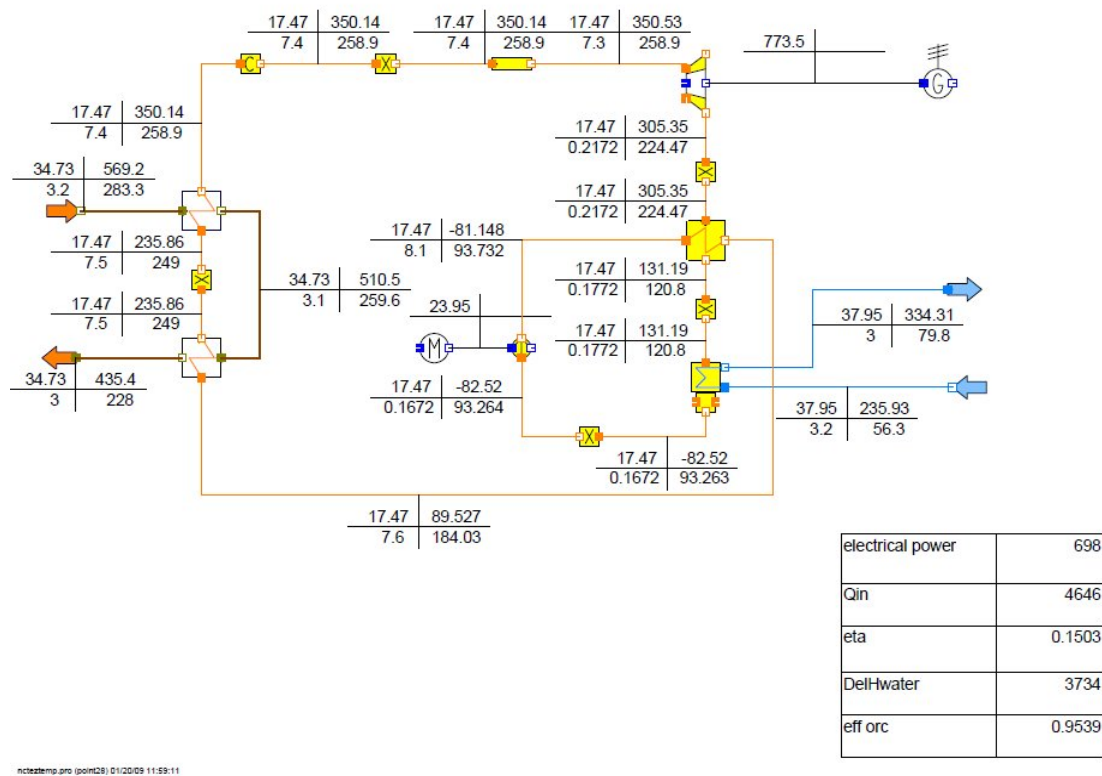


Figure A.3.28: IPSEpro flowsheet for point 28

APPENDIX A.4

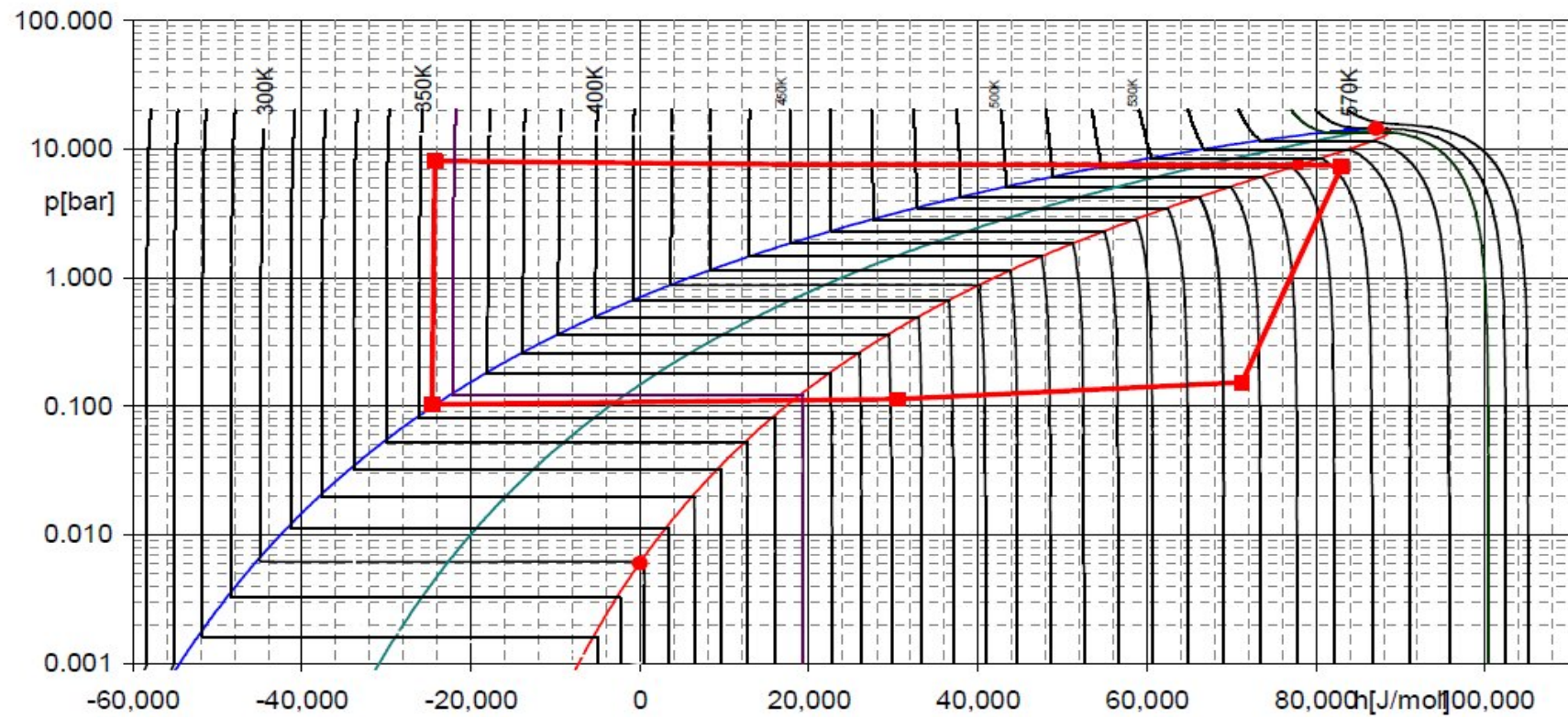


Figure A.4.1: P vs. h graphs of ORC for point 1

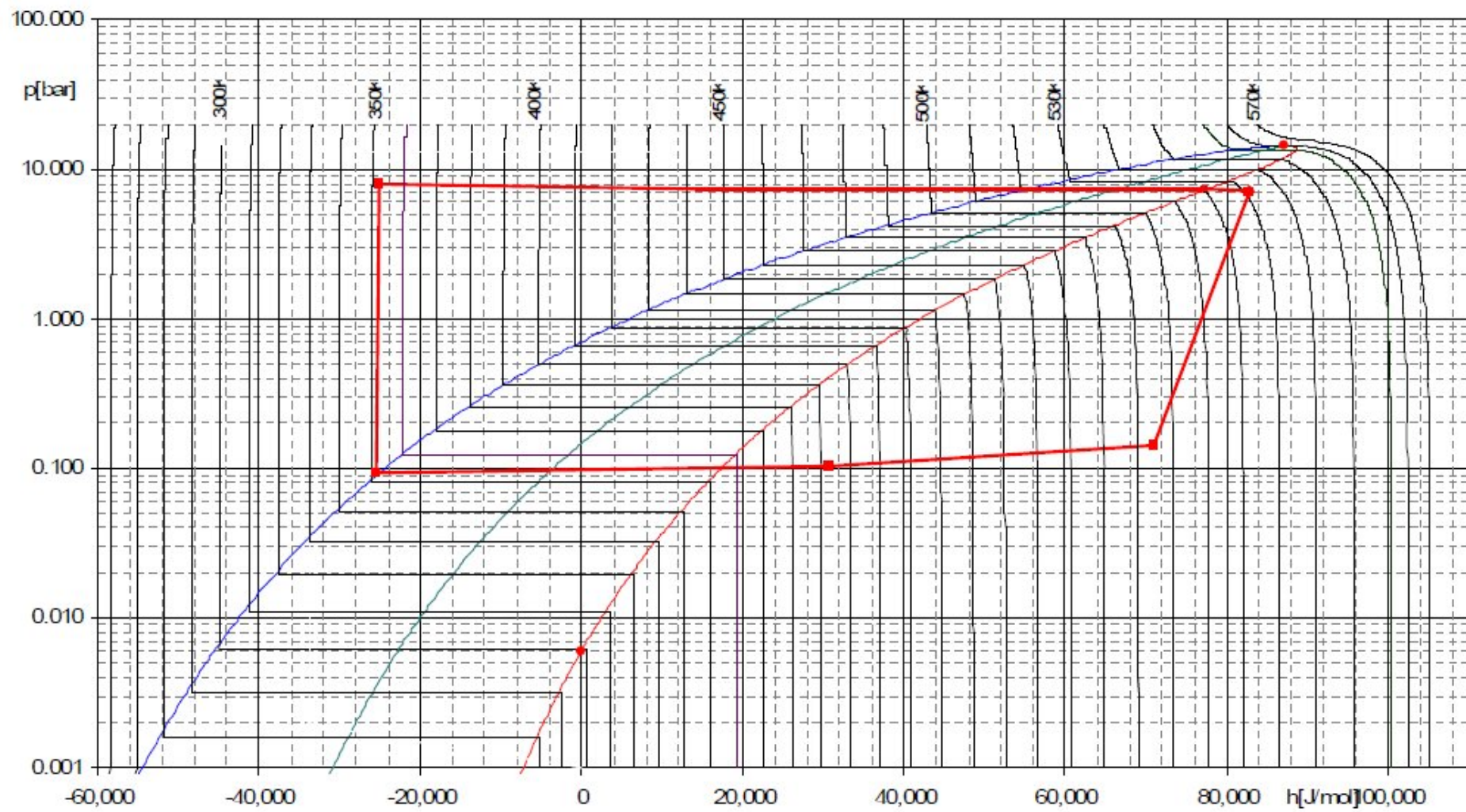


Figure A.4.2: P vs. h graphs of ORC for point 2

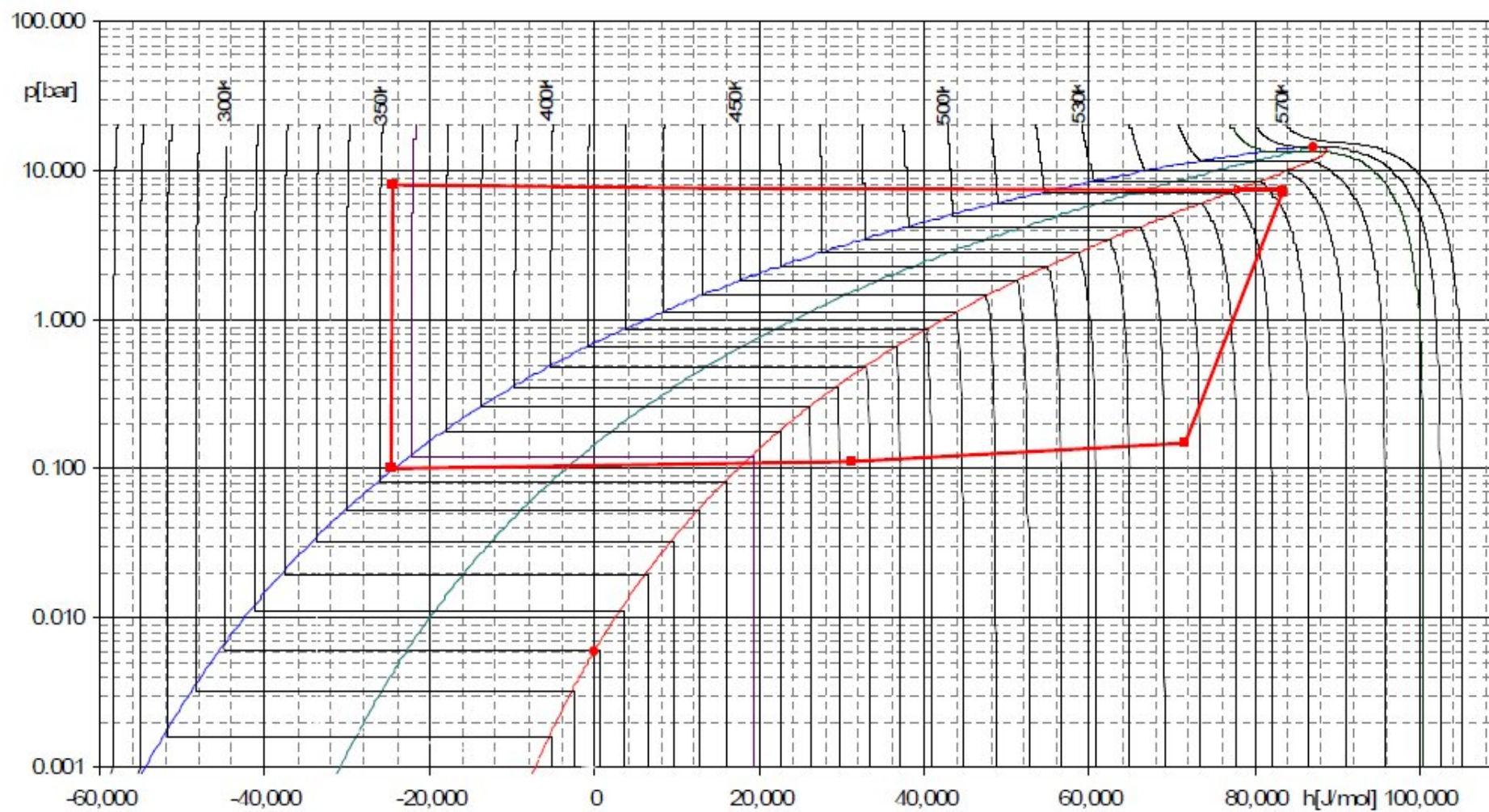


Figure A.4.3: P vs. h graphs of ORC for point 3

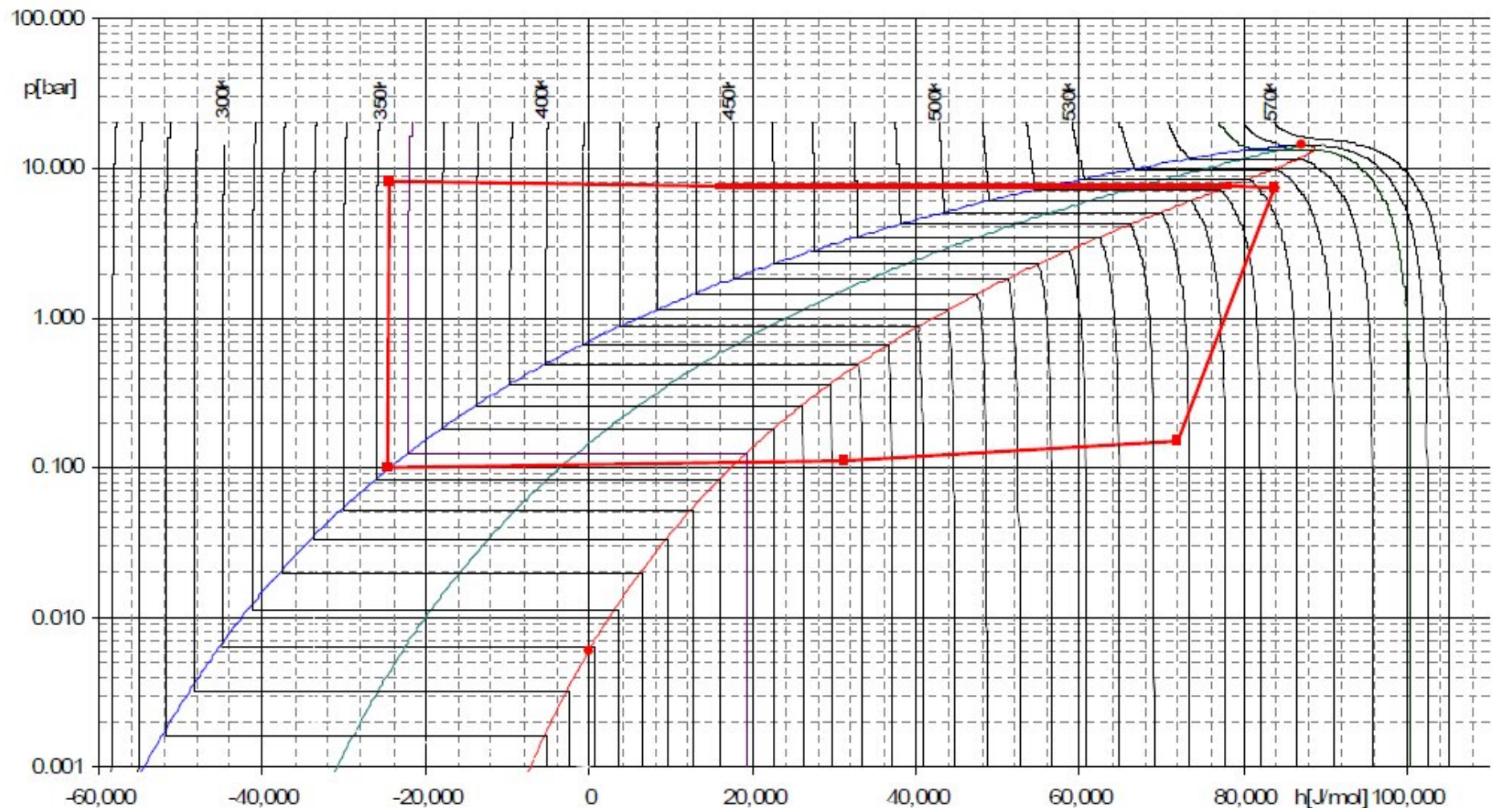


Figure A.4.4: P vs. h graphs of ORC for point 4

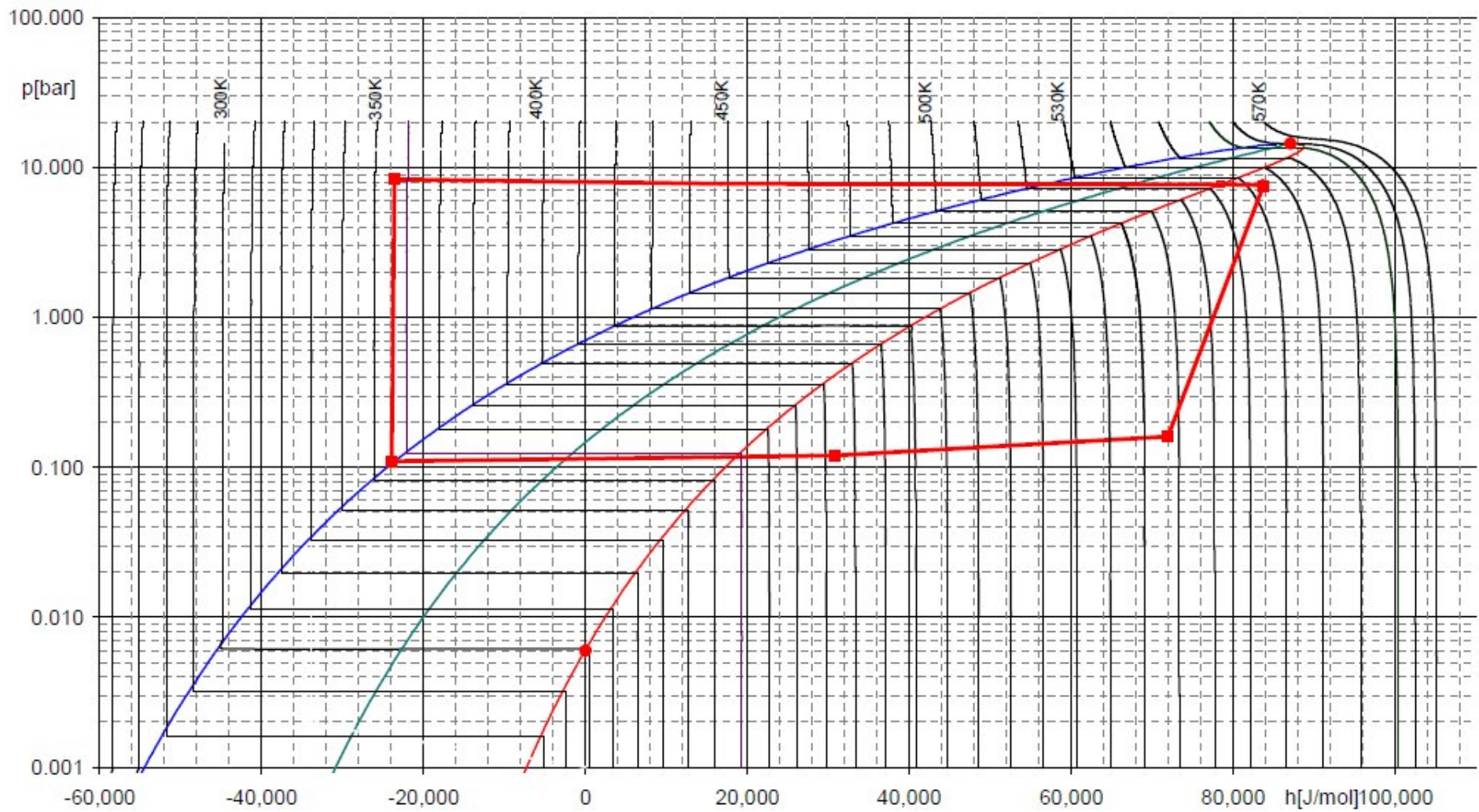


Figure A.4.5: P vs. h graphs of ORC for point 5

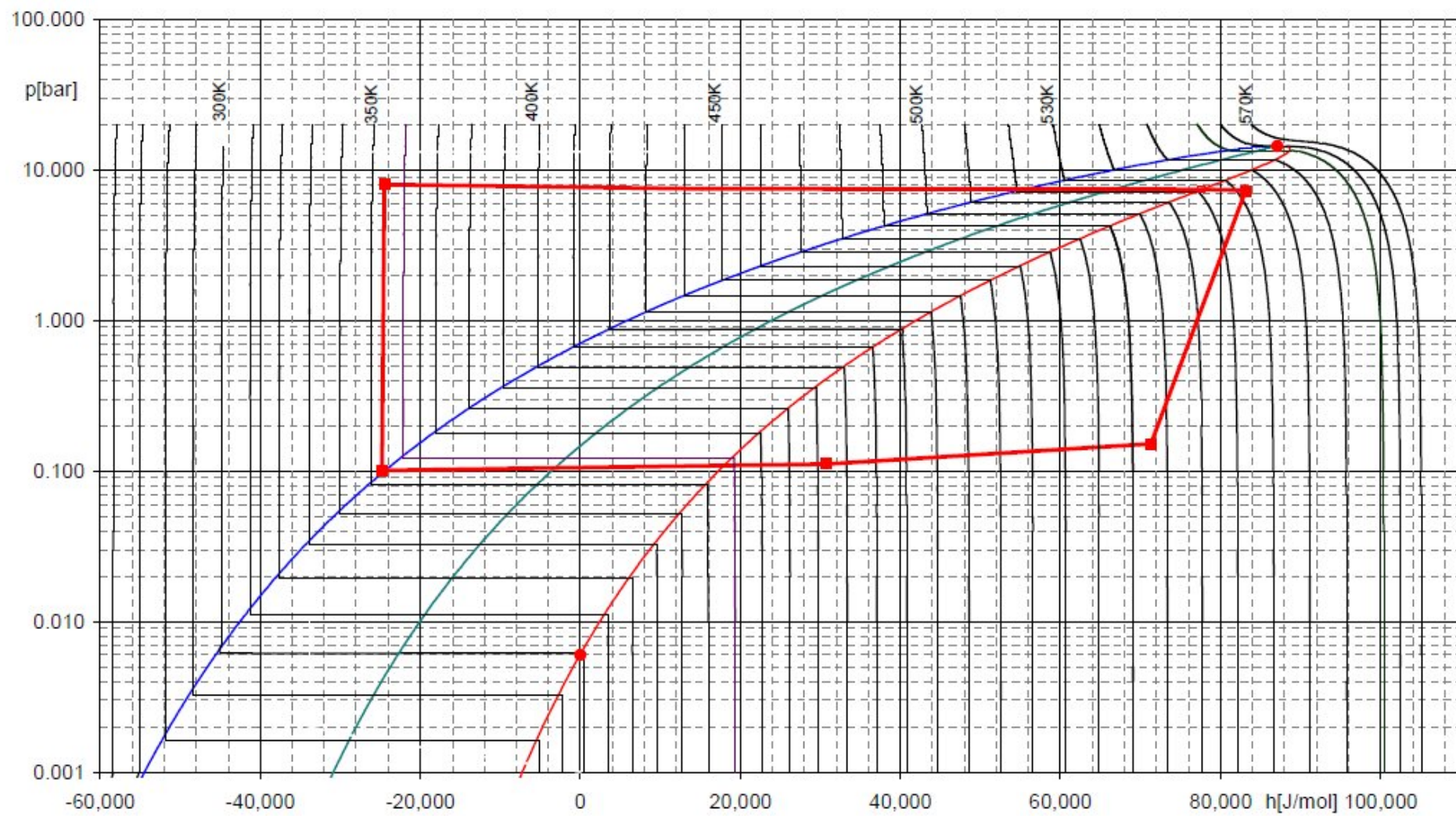


Figure A.4.6: P vs. h graphs of ORC for point 6

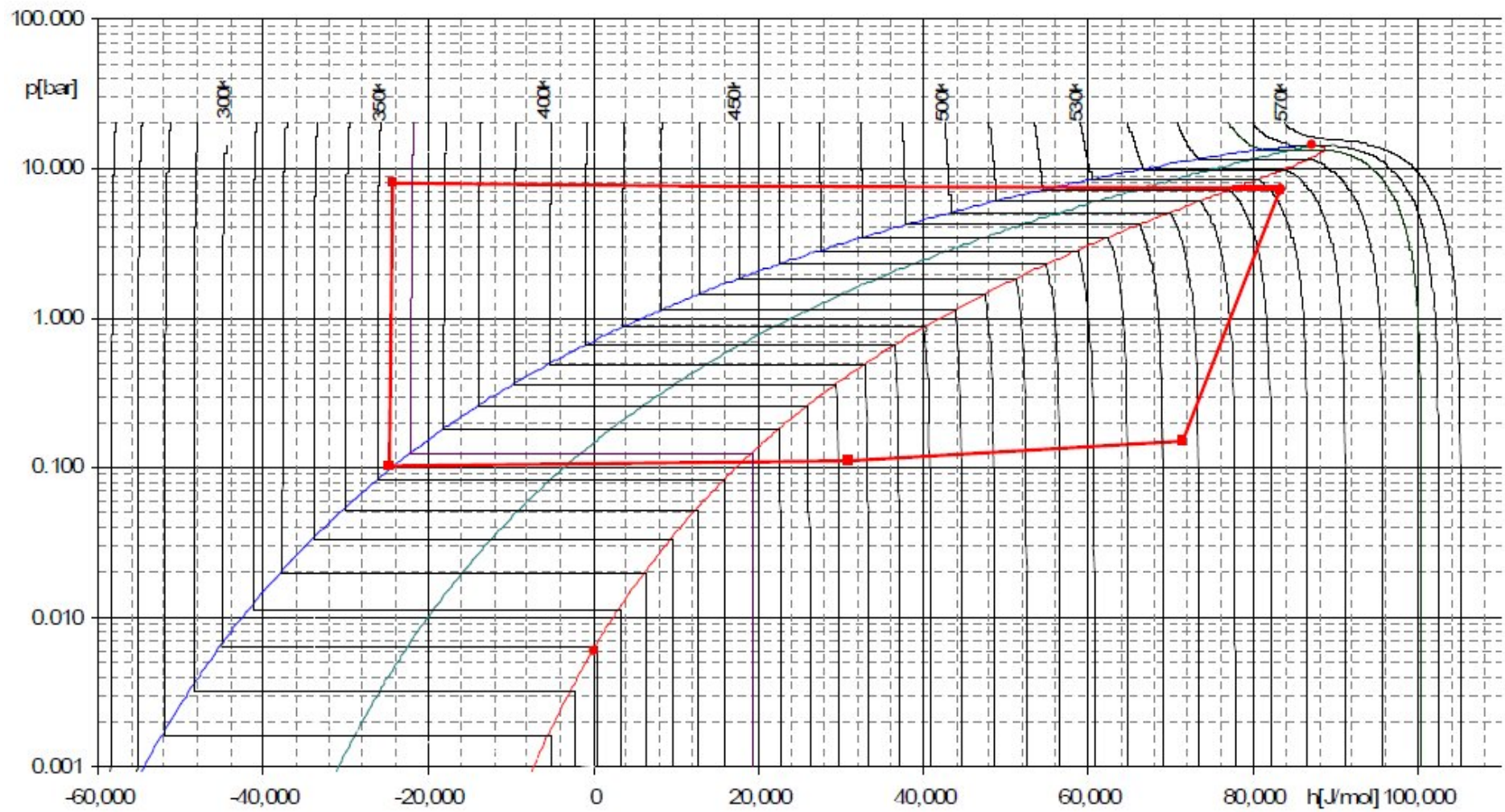


Figure A.4.7: P vs. h graphs of ORC for point 7

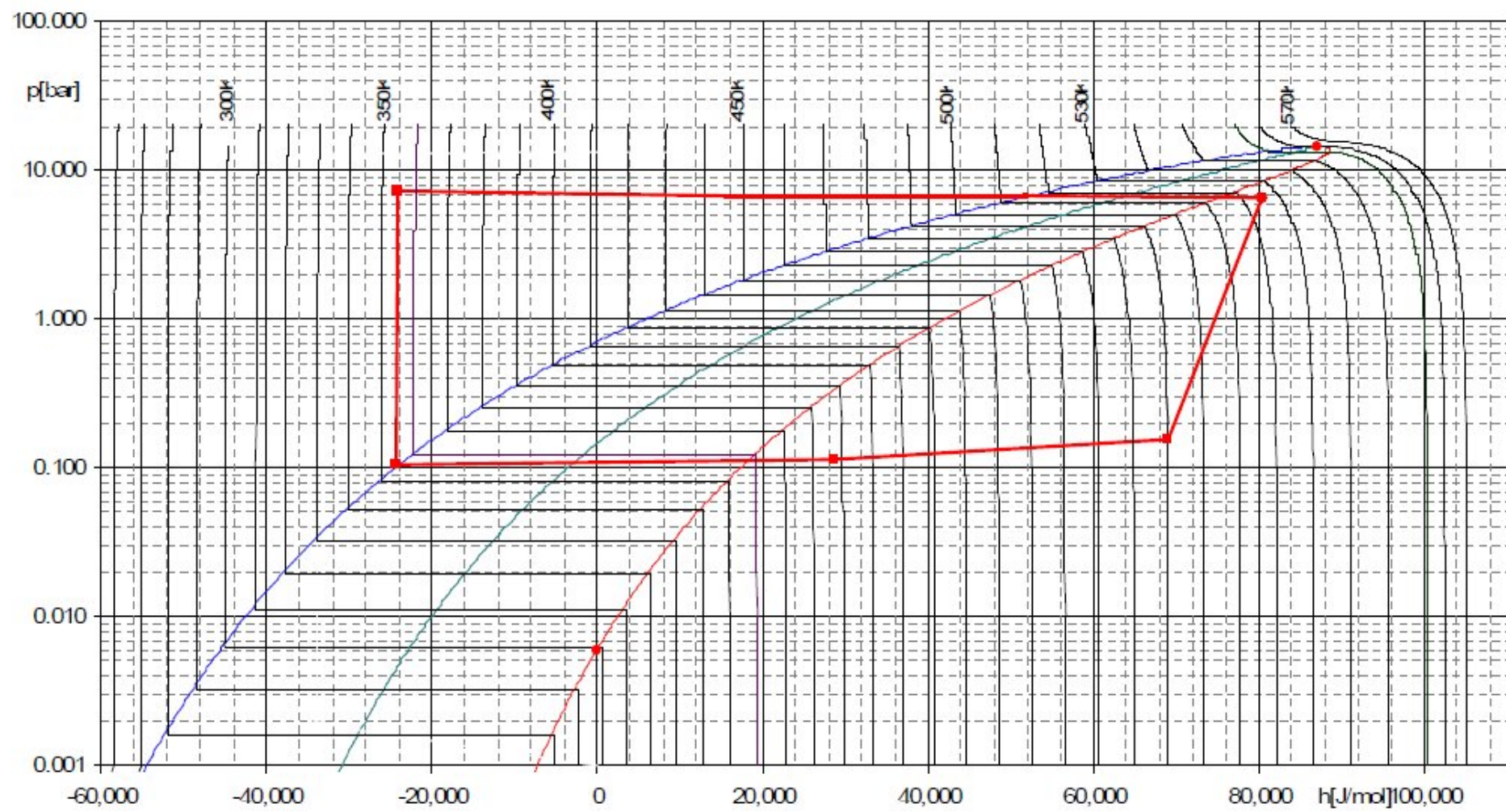


Figure A.4.8: P vs. h graphs of ORC for point 8

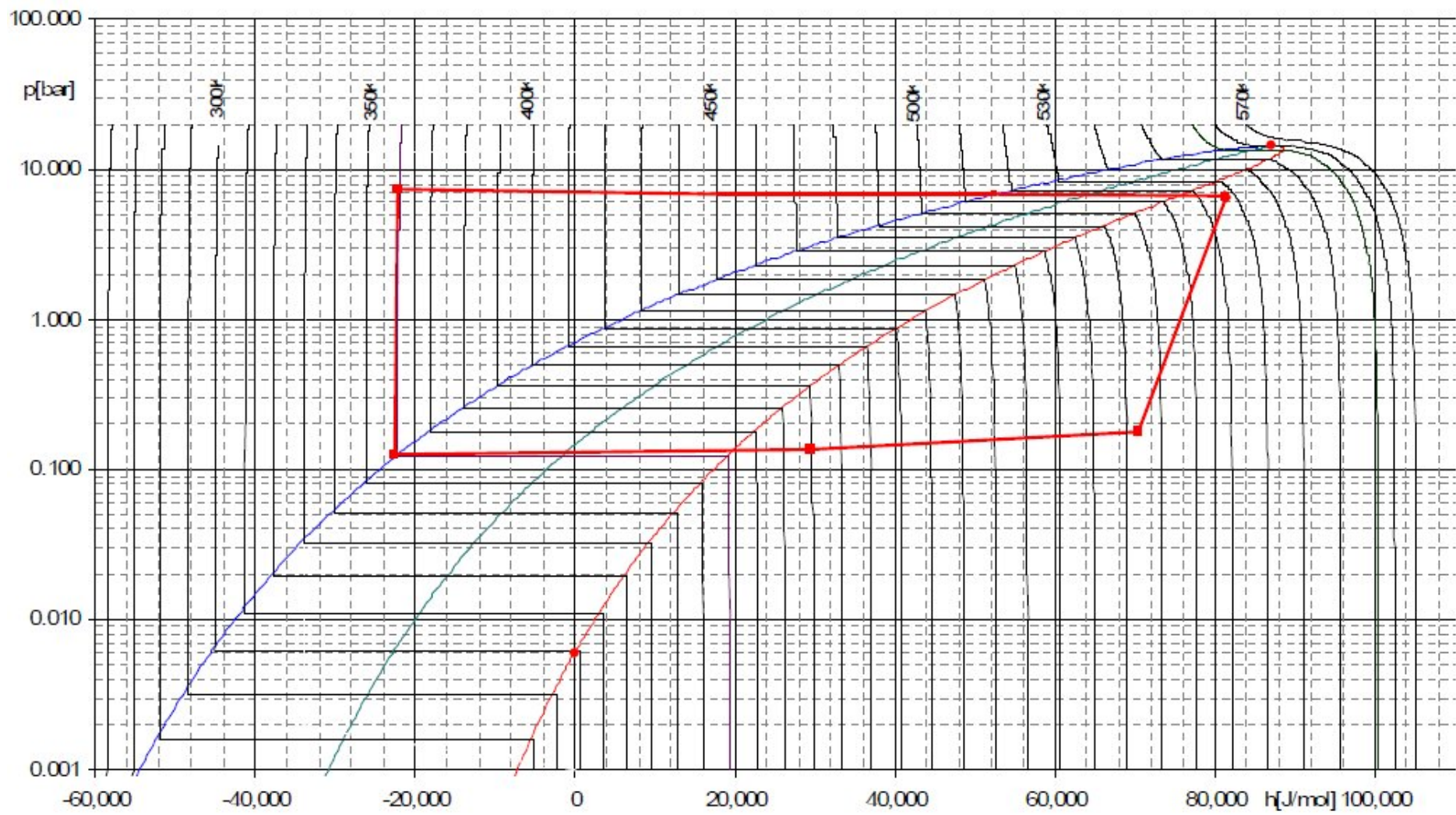


Figure A.4.9: P vs. h graphs of ORC for point 9

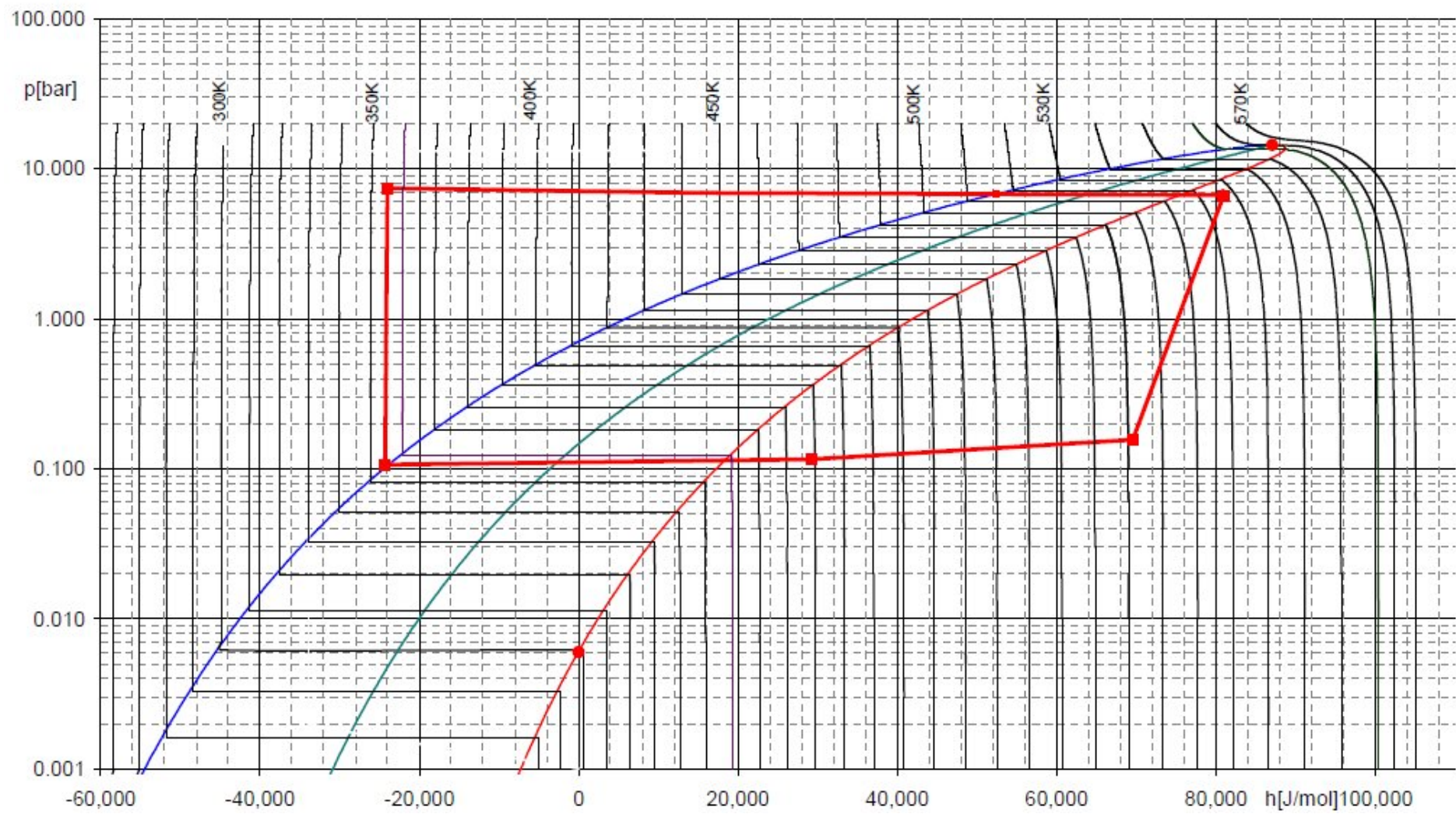


Figure A.4.10: P vs. h graphs of ORC for point 10

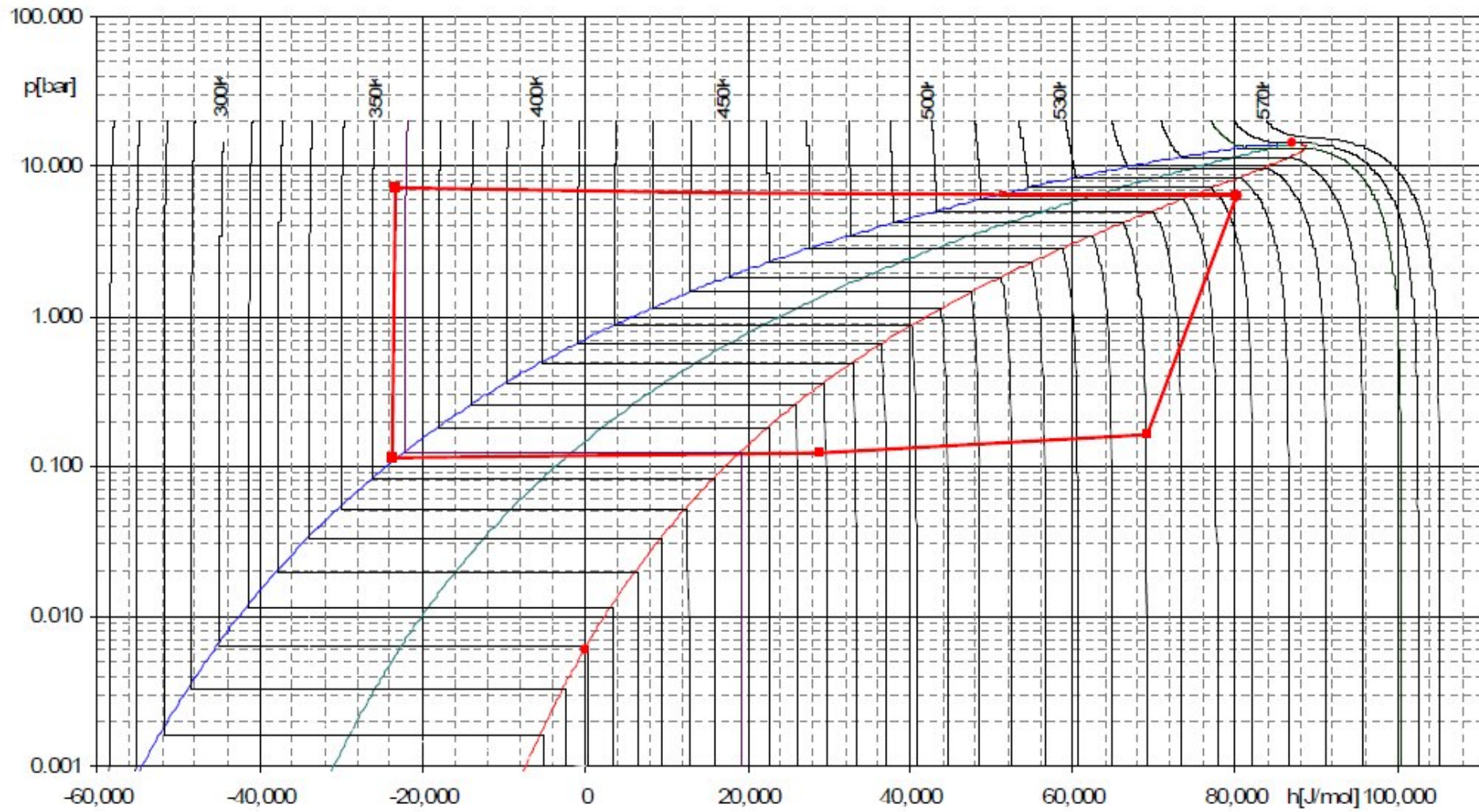


Figure A.4.11: P vs. h graphs of ORC for point 11

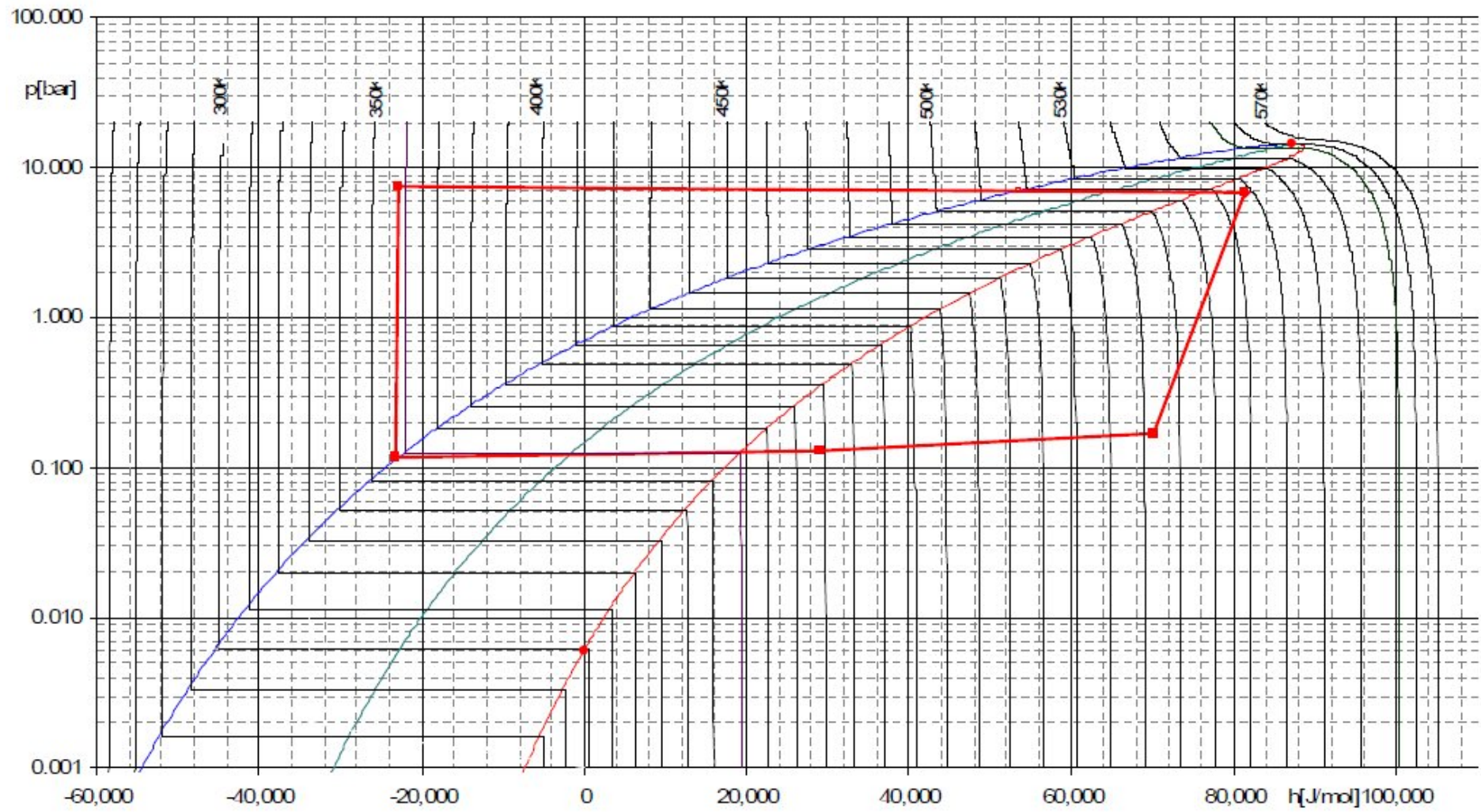


Figure A.4.12: P vs. h graphs of ORC for point 12

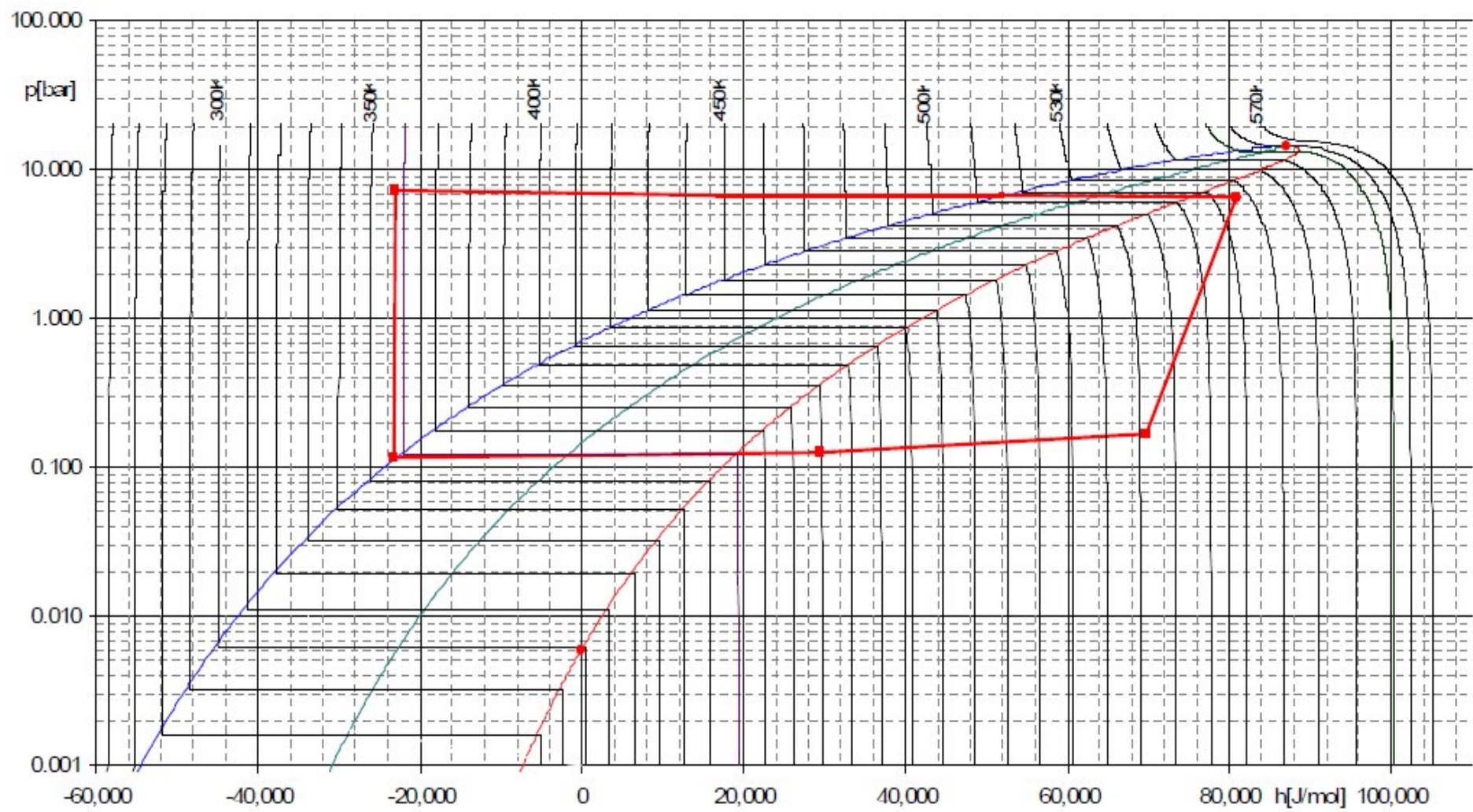


Figure A.4.13: P vs. h graphs of ORC for point 13

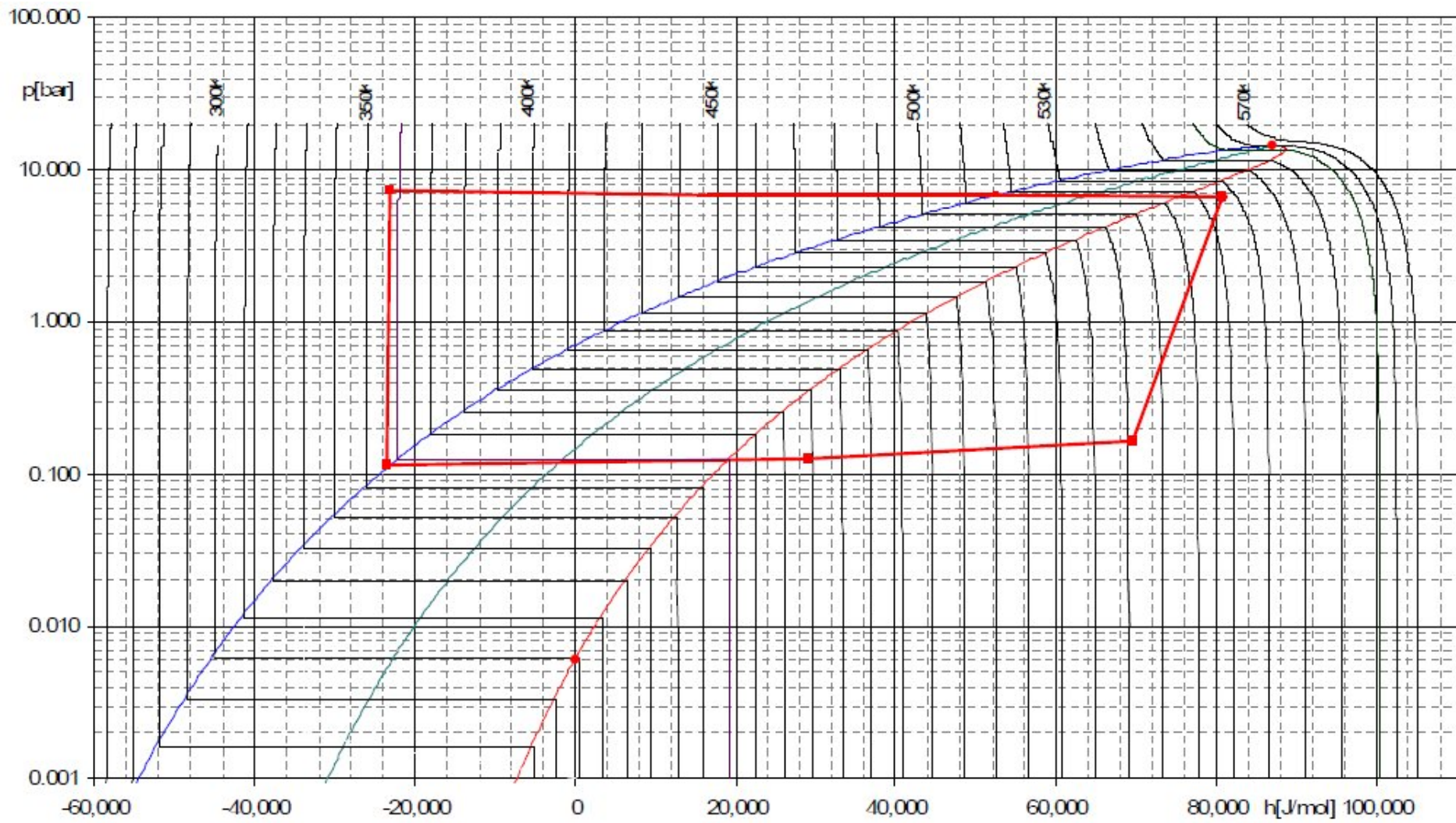


Figure A.4.14: P vs. h graphs of ORC for point 14

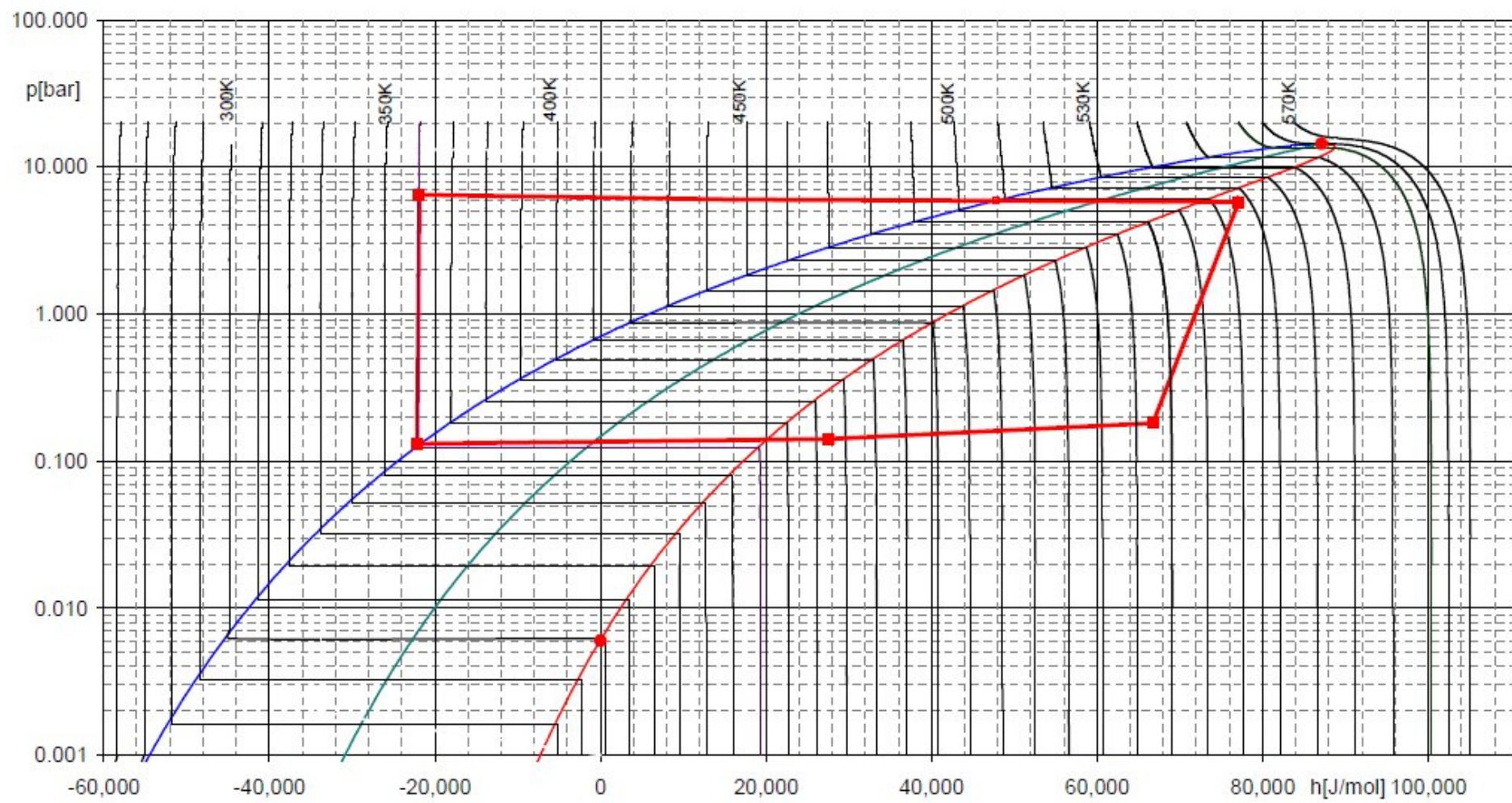


Figure A.4.15: P vs. h graphs of ORC for point 15

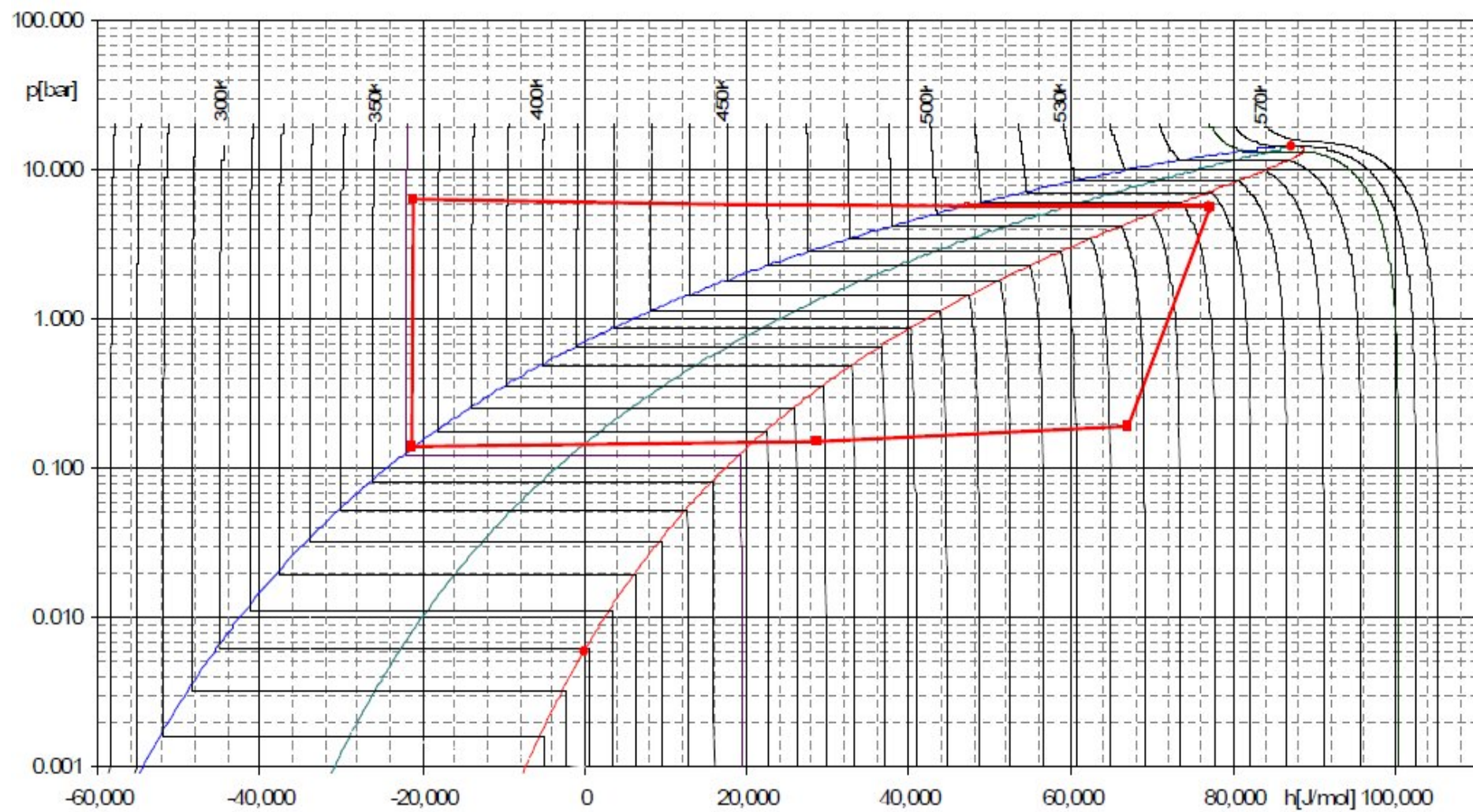


Figure A.4.16: P vs. h graphs of ORC for point 16

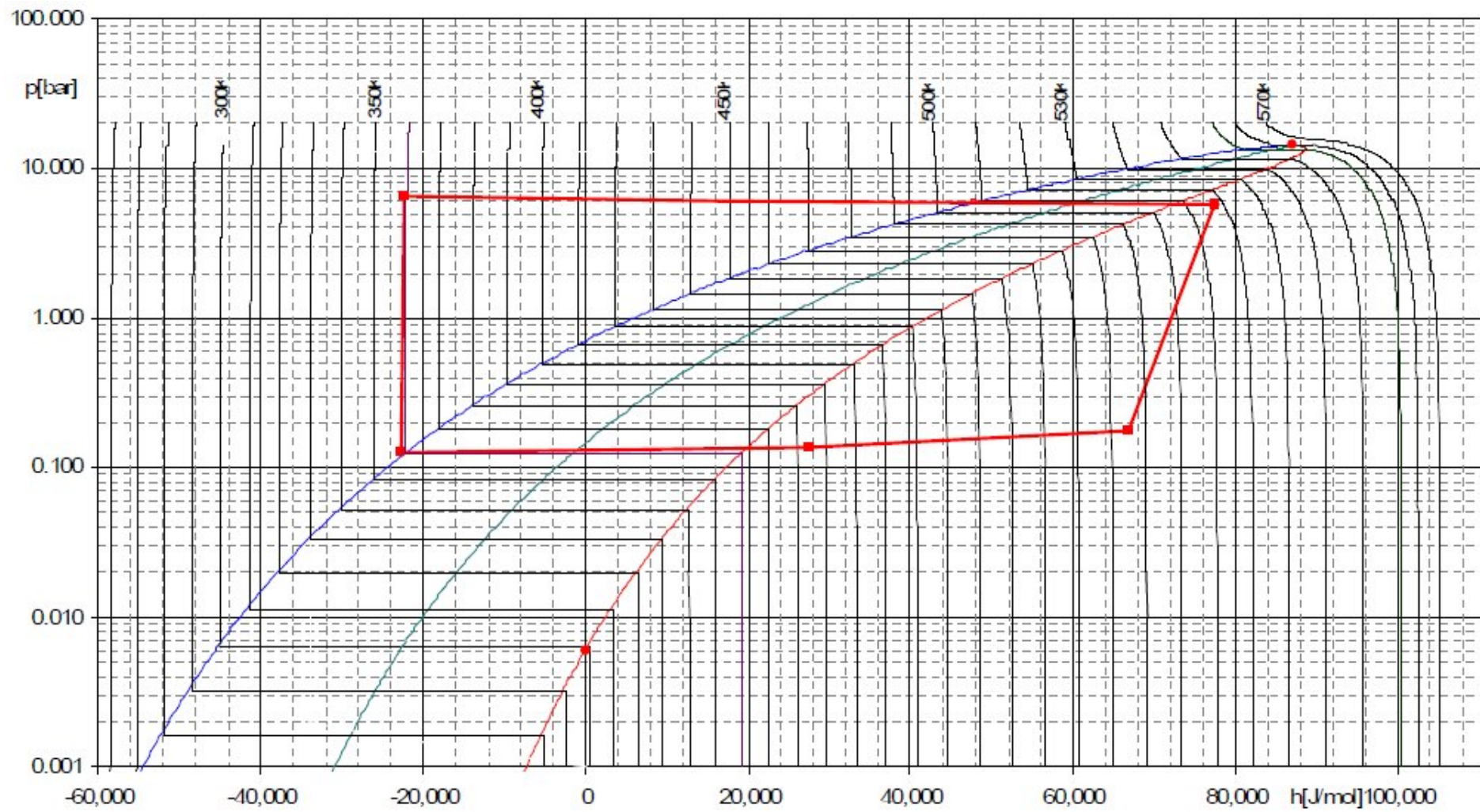


Figure A.4.17: P vs. h graphs of ORC for point 17

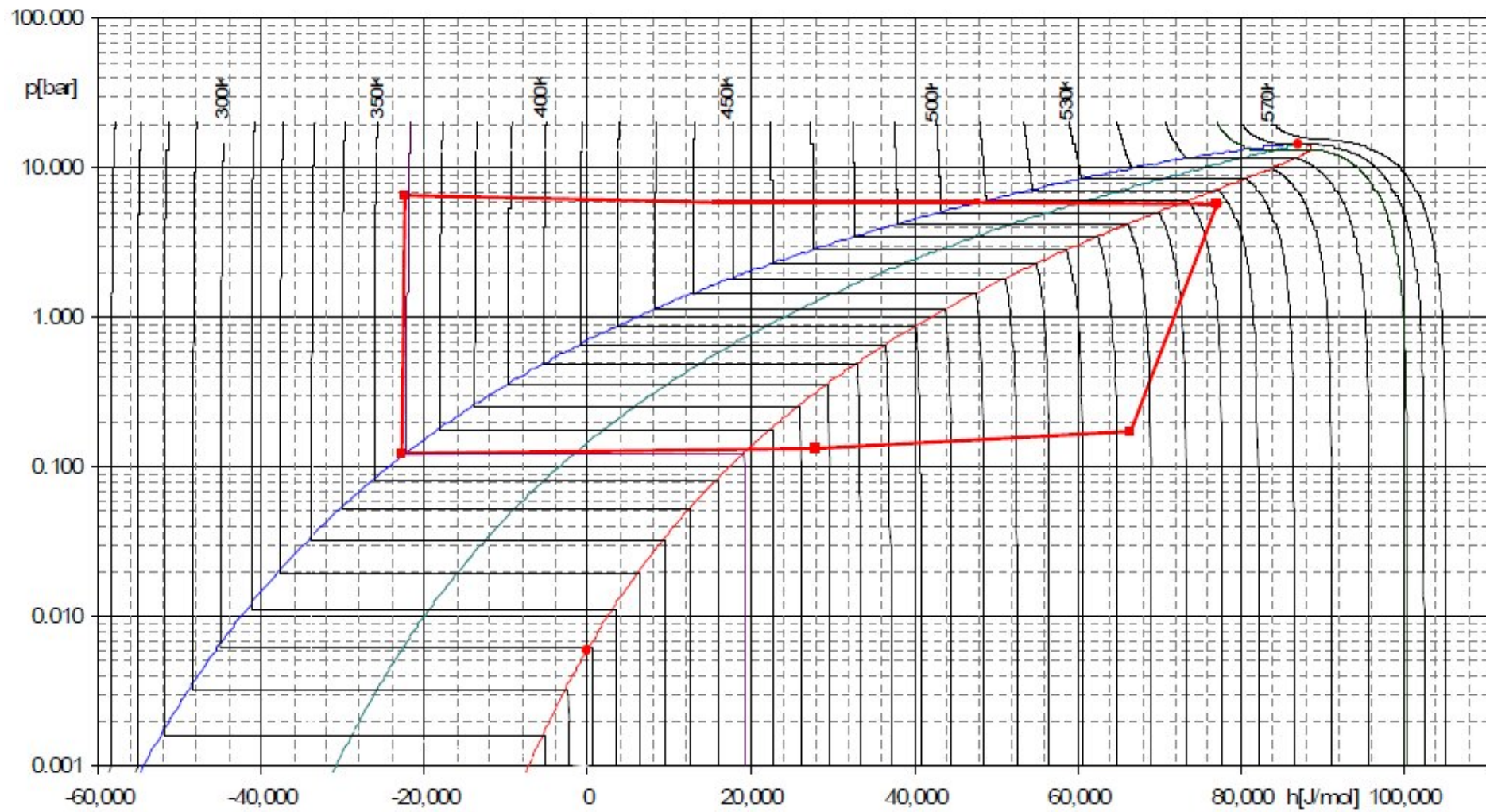


Figure A.4.18: P vs. h graphs of ORC for point 18

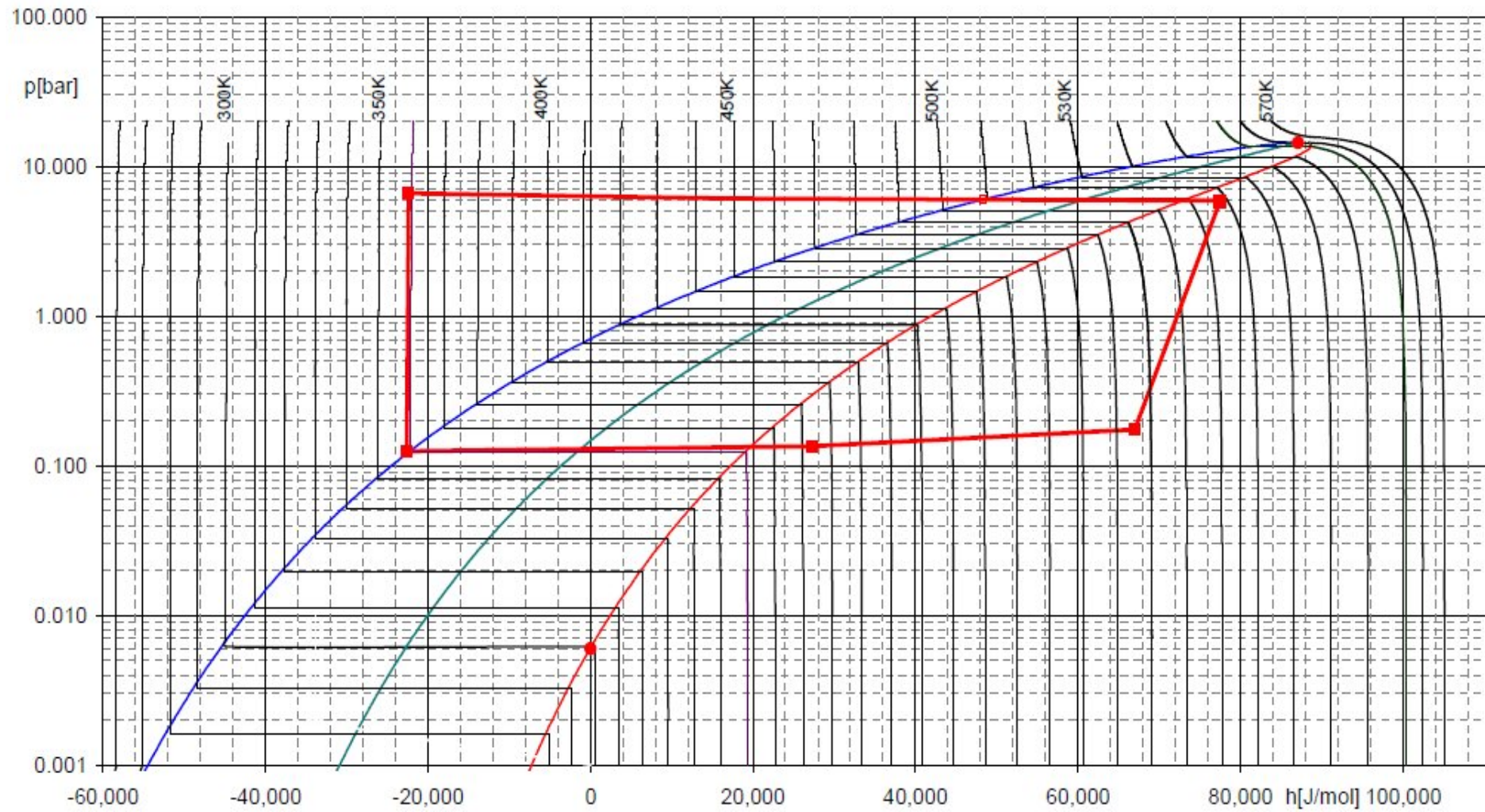


Figure A.4.19: P vs. h graphs of ORC for point 19

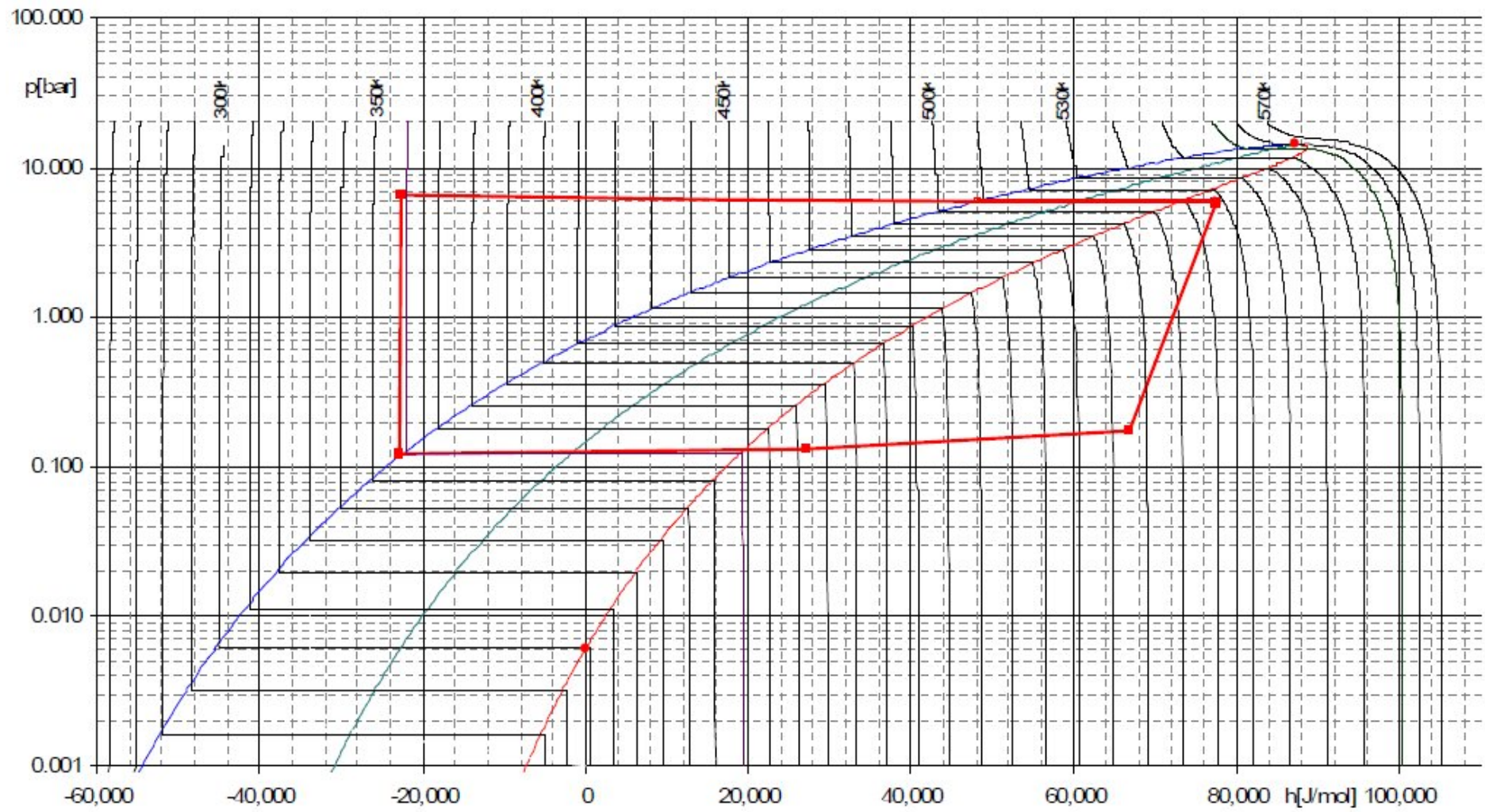


Figure A.4.20: P vs. h graphs of ORC for point 20

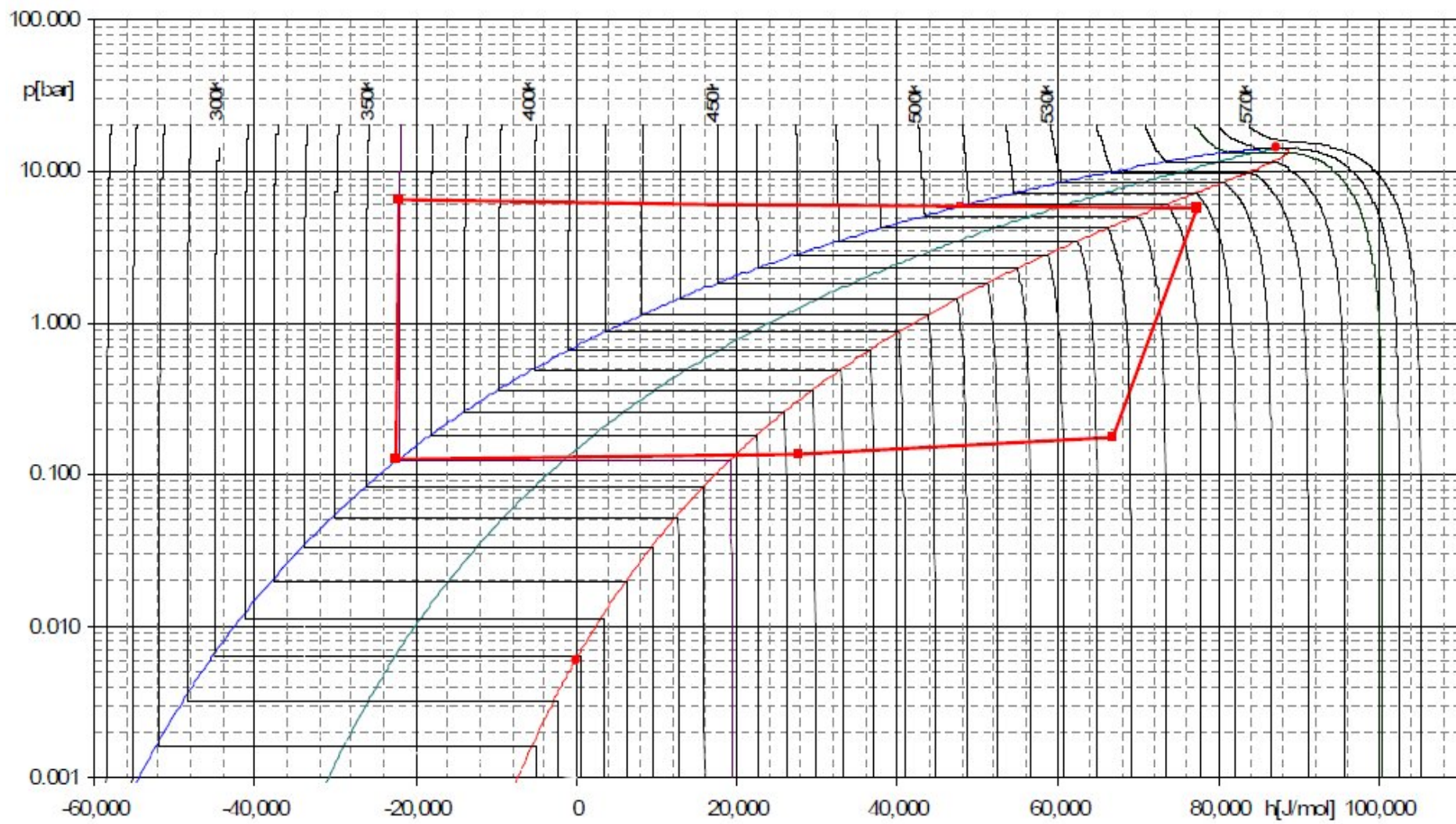


Figure A.4.21: P vs. h graphs of ORC for point 21

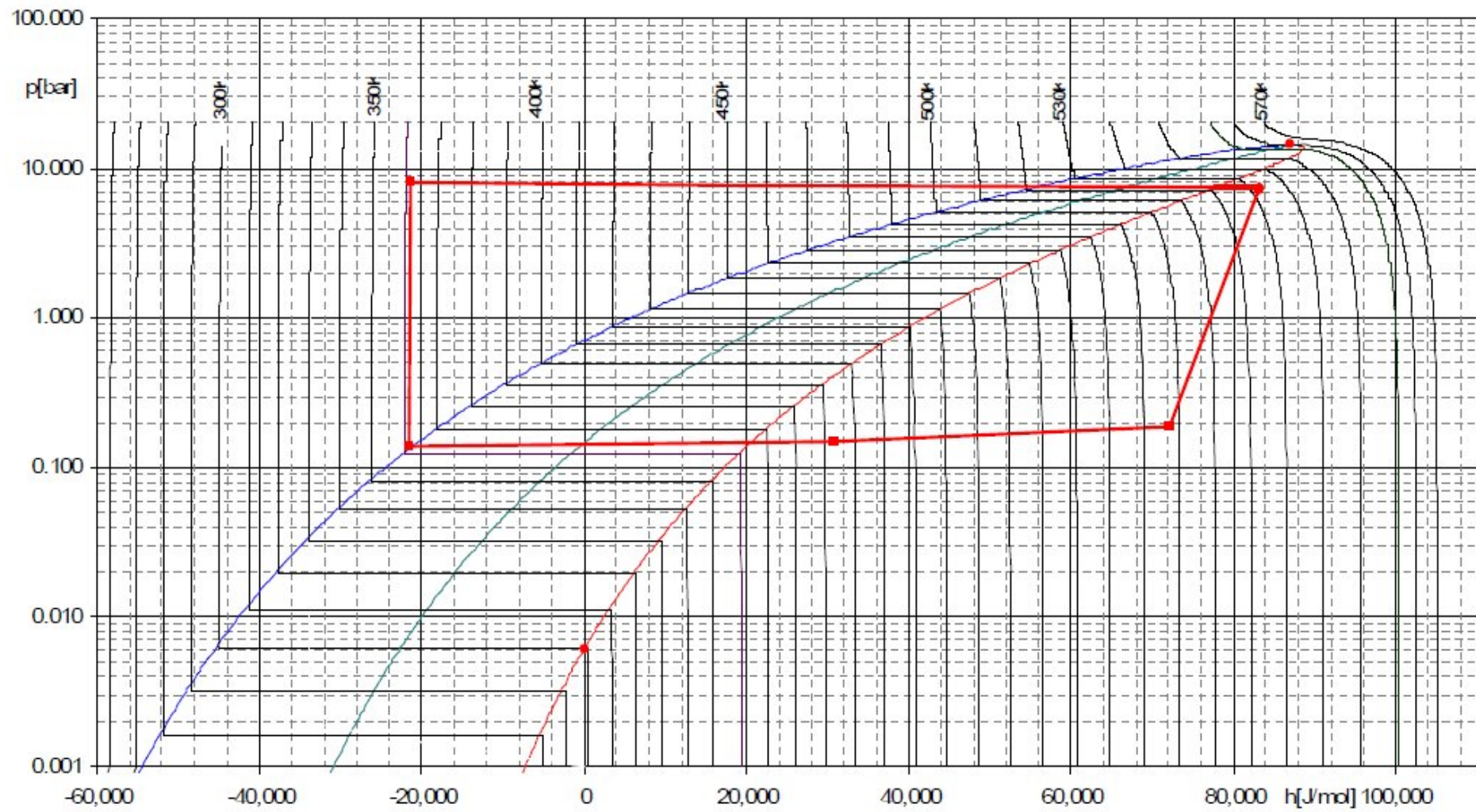


Figure A.4.22: P vs. h graphs of ORC for point 22

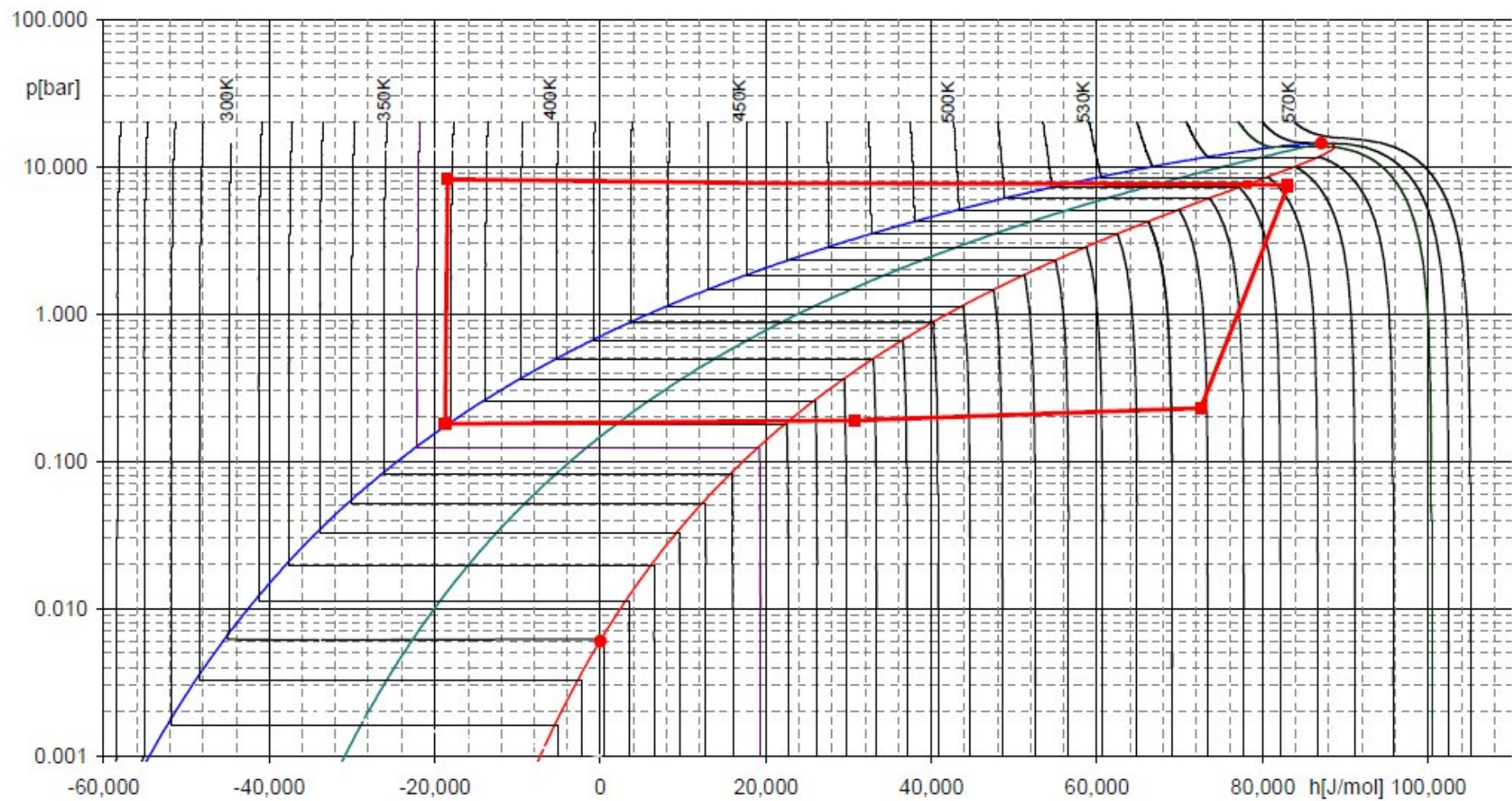


Figure A.4.23: P vs. h graphs of ORC for point 23

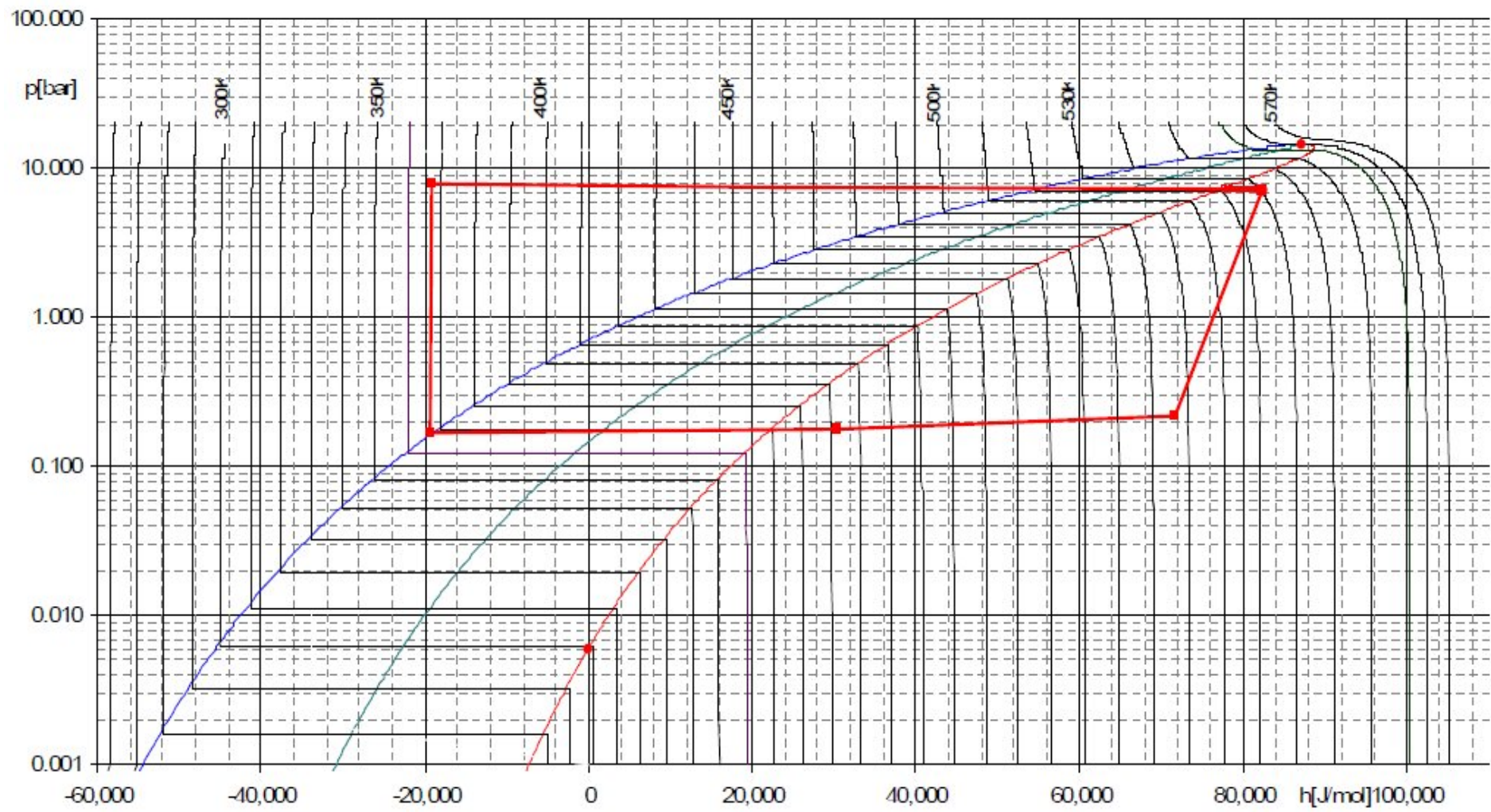


Figure A.4.24: P vs. h graphs of ORC for point 24

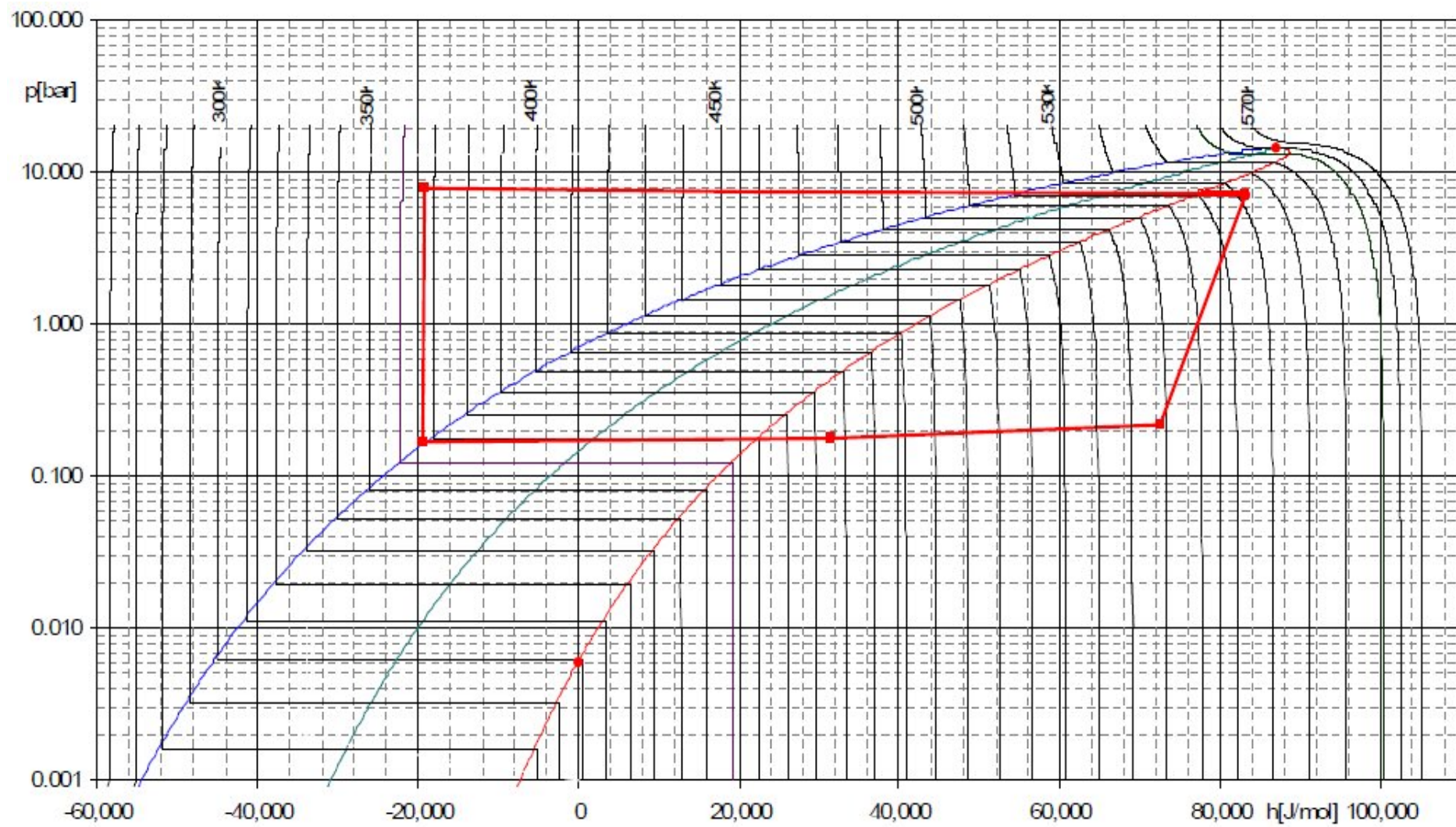


Figure A.4.25: P vs. h graphs of ORC for point 25

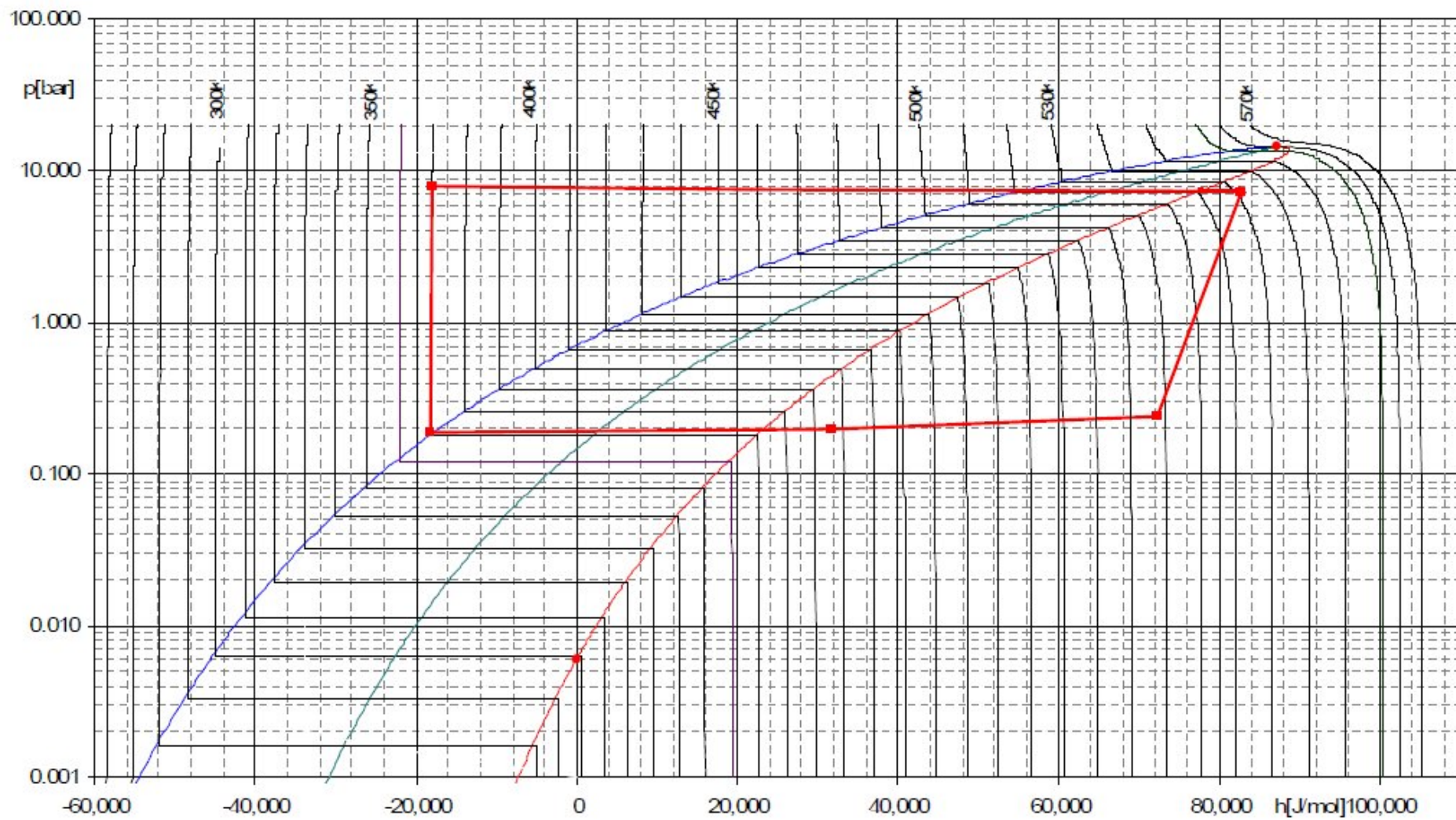


Figure A.4.26: P vs. h graphs of ORC for point 26

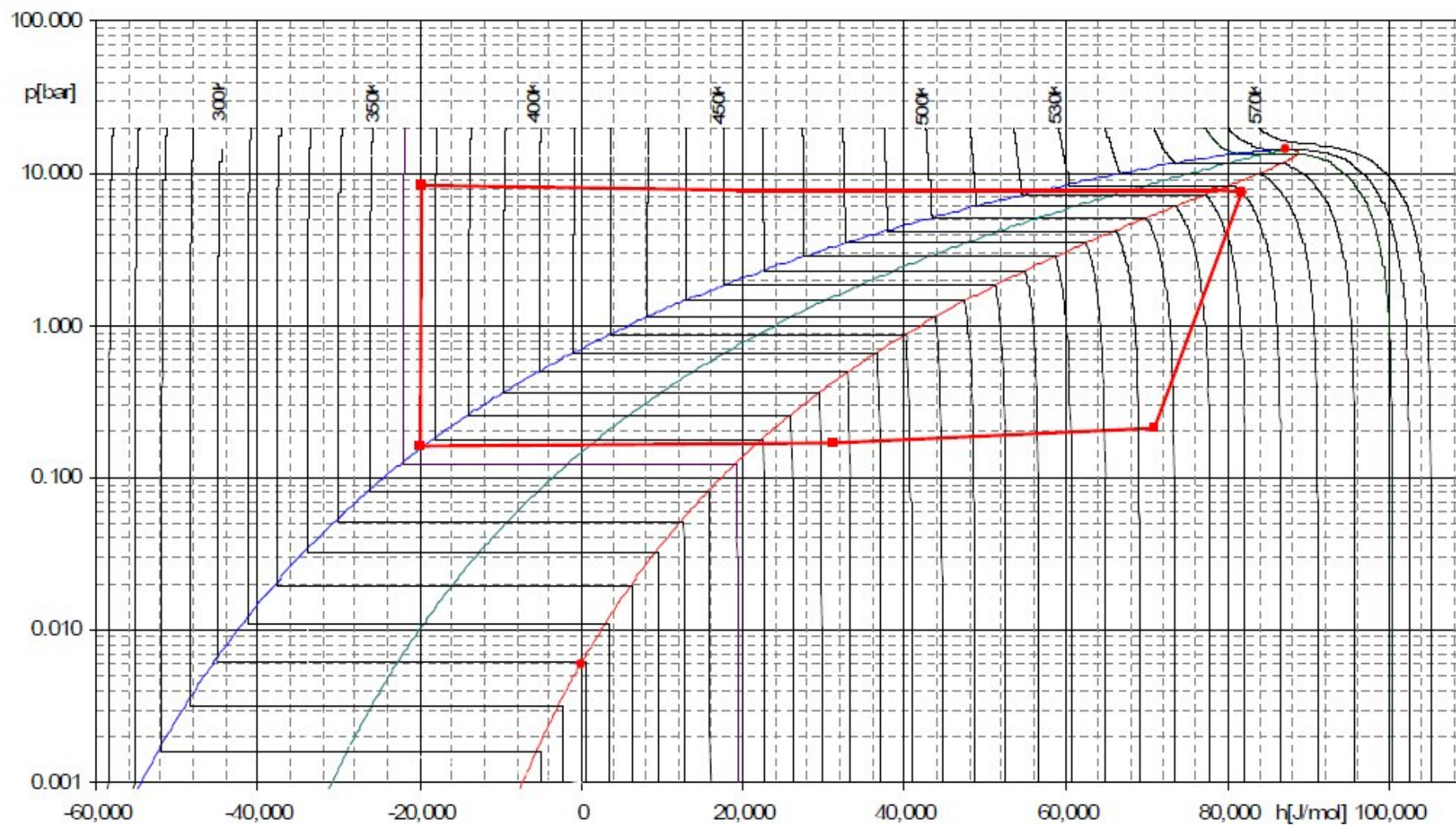


Figure A.4.27: P vs. h graphs of ORC for point 27

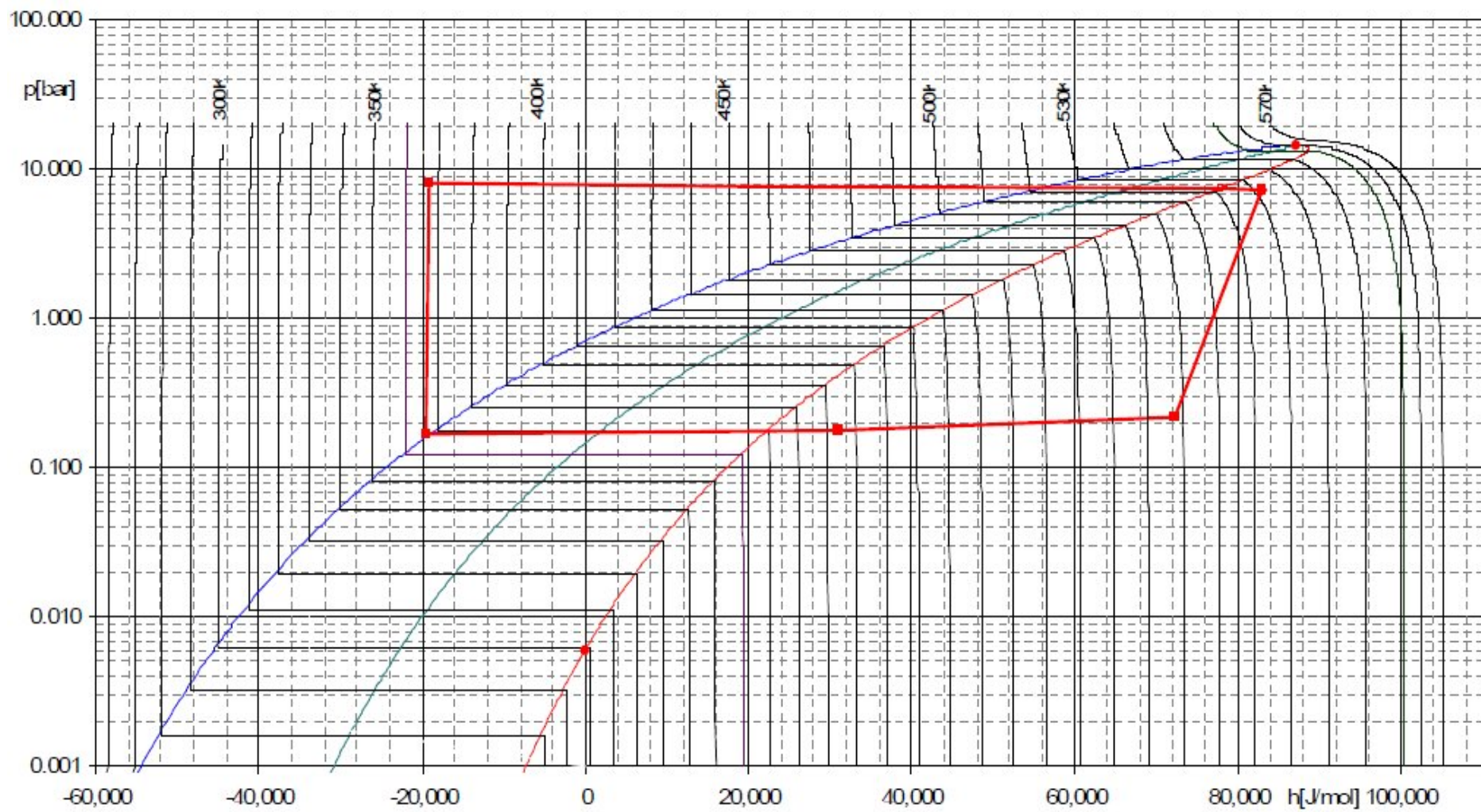
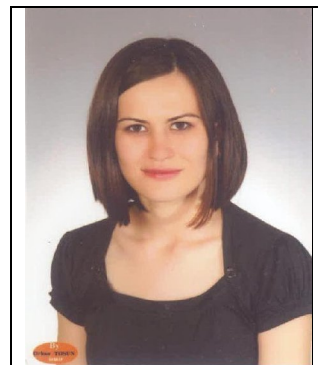


Figure A.4.28: P vs. h graphs of ORC for point 28

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- N. Camci, Y. Ceber, S. Cesur, 2007: Selection and Classification Units Used in Industry. *Proc. of UMES 2007* (National Young Researchers Symposium on Technical Education and Engineering), June 20 – 22, 2007 Kocaeli, Turkey.