Cogeneration in industrial steam systems with multiple-disk turbines

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Abstract

There are a lot of industrial and communal heat supply systems that are operated with saturated or hardly superheated steam. Steam production generally happens according to the highest pressure demand, meanwhile more or less quantity is used at lower pressure. Pressure reduction is done by throttle-valves. This is an unused potential for co-generation. Multiple disk turbines may be the expansion equipment which is suitable for realising co-generation in small- and medium scale heat supply systems. Since the construction is simple it can be produced at reasonable prices, so co-generation can be economical even at low power rates. The investigation of advantages and disadvantages of multiple disk turbines has become the subject of my presentation. Furthermore the investigation of operation conditions at different boundary conditions in case of cogeneration applications and the determination of optimal operation conditions. The same construction may be applied to a wide range of operation parameters without any modification. With variation of nozzle cross section it can be adjusted to different mass flow rate demands. The turbine can be operated even with saturated steam. Since this turbine is not sensitive to steam quality, it can be operated even with steam used in normal steam systems. There is not needed to install an extra water treatment system. Considering design and operation features of these types of turbines it can be stated that these machines may be suitable for performing economical co-generation in small- and medium sized heat supply systems. In this way the use of co-generation method may be expanded significantly.

Introduction

Rising prices of fossil fuels, dwindling resources and efforts in the field of environmental protection force society to use energy resources as efficient as possible. The best solution for fulfilling above mentioned requirements is to build and operate combined heat and power generation (co-generation) systems. At small power rates, internal combustion engine driven cogeneration systems are used nowadays. But the utilization of these systems is limited. In one way they can be operated only with clean fuels (petrol, diesel oil or gas). In another way the temperature level of the heat supplied by these systems is limited. At wide-spread small power rate steam systems (e.g. chemical and food processing plants, textile industries and hospitals) where only saturated or hardly superheated steam is generated there is no economical possibility for co-generation today. A study of industrial technologies [1] has shown that a wide field of applications can be found where low or medium pressure, saturated steam is available but for the next technology a pressure reduction has to be carried out. In most of the cases steam is generated at the highest pressure demanded in the system. (The highest pressure is generally determined by the highest saturated steam temperature demand in the system, because heat utilization happens at steam condensation at saturation temperature.) The highest pressure in these systems is in the range from 7 up to 17 bar (absolute). But more or less steam is consumed at lower pressure. Generally there are several (4 or 5) pressure level applied in case of a large chemical or food processing industry. Generally from 25% up to 50% of generated steam is consumed at significantly lower pressure than it is generated. Nowadays throttle valve are generally used in these systems for pressure reduction. Multiple disk turbine is intended to use for utilization of pressure drop.

Expansion Behaviour of Saturated Steam

Following cases are typical cases of expansion:

Throttling:
In this case no power is gained from expansion.

$$P_e = 0$$

Efficiency of this expansion equipment would be 0%,

$$\eta_T = 0$$

After this expansion steam will be slightly superheated.

$$h_{in} = h_{throut}$$

This is the case of expansion at throttle-valve pressure reducers.

Isentropic expansion:
This is the expansion, where the theoretical maximum available power is gained from the pressure reduction. Efficiency of this expansion equipment would be 100%.

$$\eta_T = 100\%$$

Isentropic (theoretical) power can be derived as:

$$P_{is} = \dot{m}_{steam} \cdot (h_{in} - h_{isout})$$

After this expansion steam will be in saturated vapor-liquid mixture area.

Real expansion:
This is the real expansion line using a real expansion equipment, e.g. a turbine. Power of the turbine can be derived as:

$$P_{real} = \dot{m}_{steam} \cdot (h_{in} - h_{realout})$$

Efficiency of the turbine can be derived as:

$$\eta_T = P_{real} / P_{is} = \Delta h_{real} / \Delta h_{is}$$

After this expansion steam can be slightly superheated, saturated, or in saturated vapor-liquid mixture area, depending of expansion efficiency. At about $\eta_T = 30\%$ turbine efficiency exhaust steam will be saturated.

During the expansion, when the expansion line has crossed the saturated steam-line and expansion happens in the vapor-liquid mixture area, a change of phase should begin to occur. At this point the random kinetic energy of the molecules has fallen to a level which is insufficient to overcome the attractive forces of the molecules and some of the slower moving molecules coalesce to form tiny droplets of condensate. When the expansion process is rapid, and flow velocity is very high, this process does not have time to occur. The achievement of equilibrium between the liquid and vapor phases is therefore delayed, and the vapor continues to expand in dry state. This state is called *supersaturated,* or *supercooled* [5]. Because these states are not states of stable equilibrium, they are called metastable states. The name is originated from the idea that this is not an equilibrium state, but it cannot be called unstable as well, because an infinitesimal disturbance will not cause a major change of state. This metastable state, depending on velocity and pressure level, can exist till 3%-5% of liquid content of steam. The delay in condensation leads to a build-up of molecular cohesive forces which finally results in sudden condensation at many points. This condensation occurs suddenly, with an increase of both entropy and pressure. After the beginning of condensation saturated steam consists of increasing amounts of water droplets during expansion.

Expansion Utilization Possibilities

Reciprocating steam engines cannot be used because increasing water content in the steam can cause serious damage at the crank mechanism or at the piston, when the water volume is greater than the clearance volume of the cylinder, because liquid is practically not compressible.

Bladed turbines are sensible to liquid content in steam. In one way turbine efficiency is decreasing, and in another way droplets can cause erosion on the turbine blades. In order to avoid serious erosion problems at turbines used in nuclear power stations, where a large part of steam expansion happens at liquid-vapor mixture area, dewatering is used between every turbine stage. This is a very expensive solution.

Both solutions have a higher quality demand for water than needed for normal boiler operation.

Demands for a small power rate expansion machines operated with saturated steam:

For a small power rate operation a plain and robust construction is needed [6].

To avoid large amount of water droplets in the steam, end state should be close to the saturation line. This means that turbine efficiency should not be higher than $\eta_T = 50\%$. This will not cause higher losses, because heat is utilized after expansion.

To avoid erosion the streamline should not bend sharply.

At those pressure drops where our turbine is intended to operate, this maximum available power is about 5-15% of the total energy content of the steam. When turbine efficiency is about: $\eta_T = 30\% - 40\%$. Generated energy by this turbine is about 2-5% of total energy content of steam. Friction-, heat- and energy conversion losses give about 0.5-1% that are not recoverable as useful heat. Extra boiler loss ratio to the extra fuel power is the same as original boiler loss over original fuel power and equal with the applied boiler efficiency. Fig. 2 shows the energy flow (Shankey) diagram of our turbine-generator set applied for pressure reduction. Fig. 3 shows efficiency variation of cogeneration from pressure reduction against additional firing power in the function of nominal power of the system [2].

Description Of An Adequate System

The main goal of the system is to replace throttle valve pressure reducers with expansion utilization equipment. Reducing steam pressure is a common task in these systems. Nowadays generally throttle valves are used for this purpose. In this case the possibility for generating electricity is not used. We have developed a system for exploiting the power generation potential by pressure reduction in industrial heat supply systems. The purpose was not to reach the highest possible efficiency, but it was to reach economical operation at above describe circumstances for a wide range of working medium parameters. We have kept in view the flexible applicability. This system works as a pressure reducer installed into a heat supply system, while it generates electricity and feeds electricity back to mains.

We have chosen a special radial type turbine, which is different from conventional bladed turbines. The turbine rotor con-

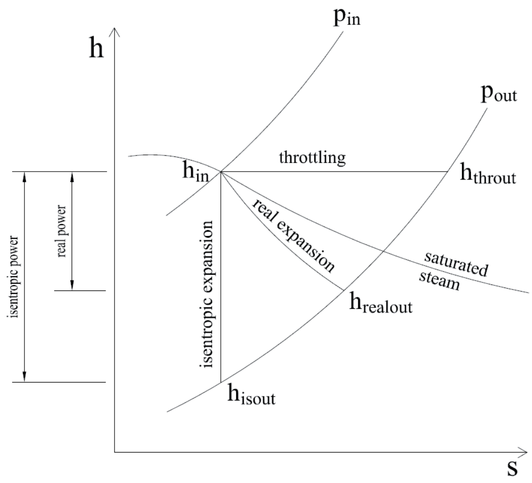

Figure 1. Saturated steam expansion cases in h-s chart

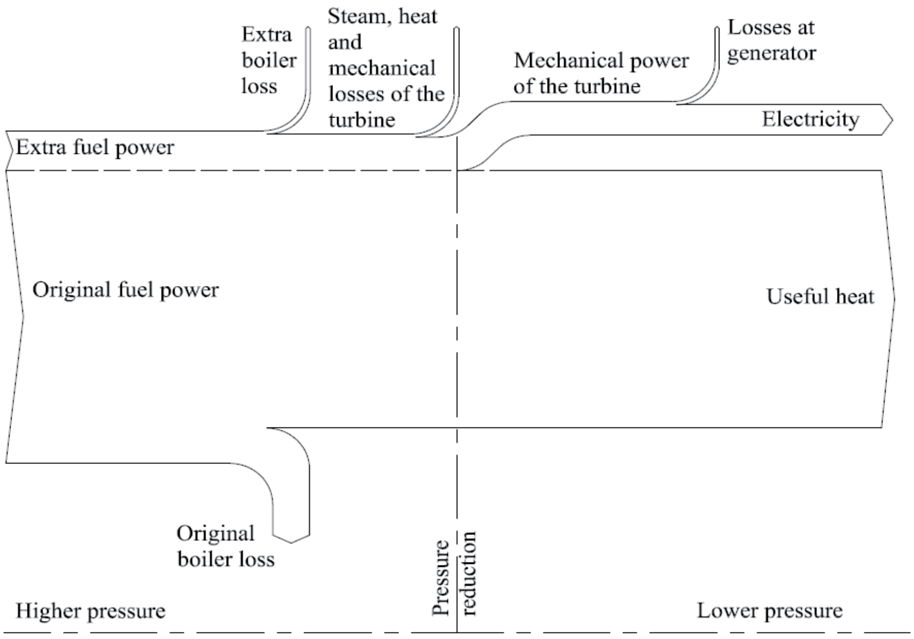

Figure 2. Energy flow diagram of pressure reduction with and without cogeneration

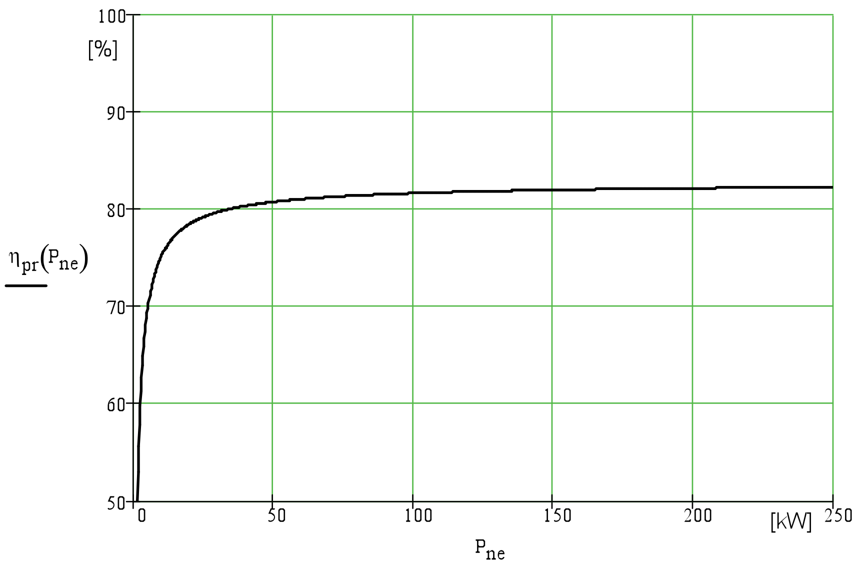

Figure 3. Efficiency variation of cogeneration from pressure reduction against additional firing power in the function of nominal power of the system

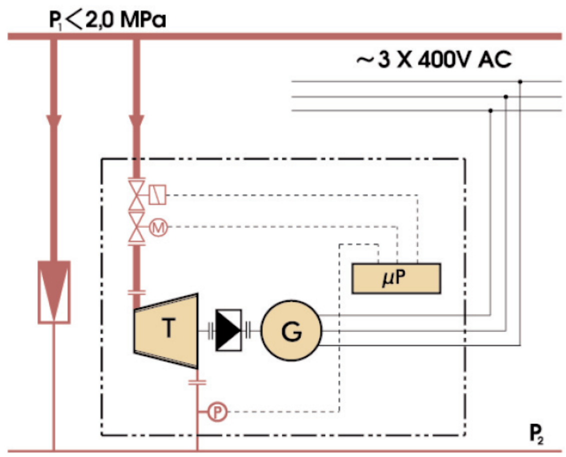

Figure 4. Functional diagram and connection of the system

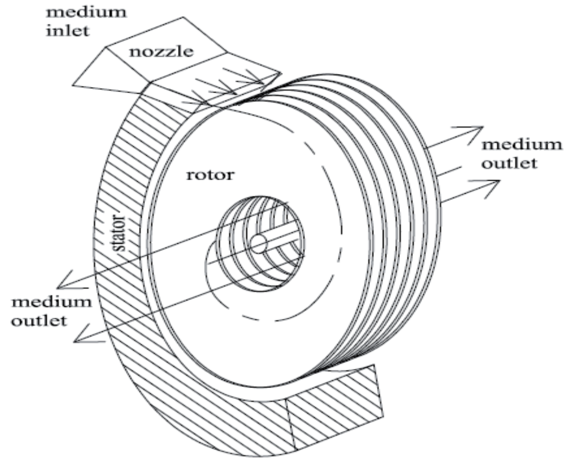

Figure 5. Cross-section of the multiple disk turbine

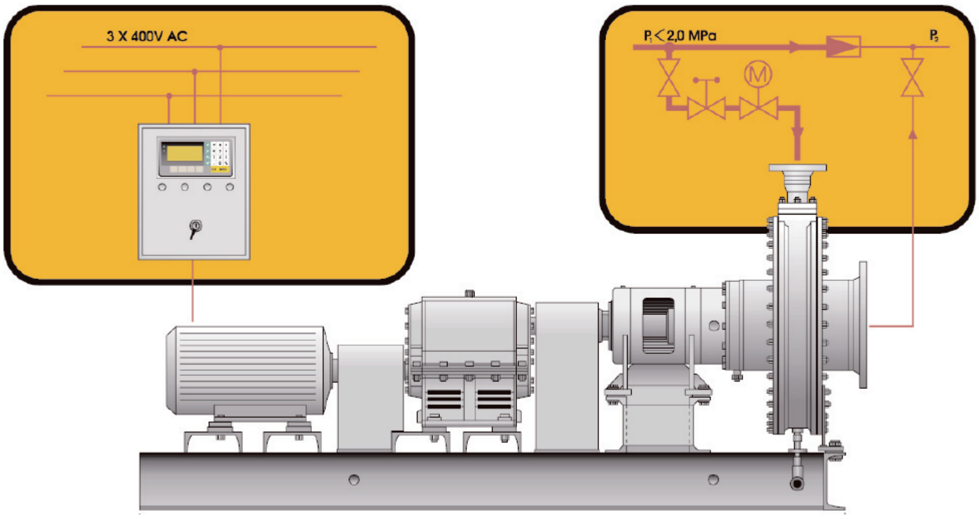

Figure 6. Side view and functional connection of turbine generator set.

sists of a number of thin, smooth, flat, parallel disks arranged perpendicular to a shaft and fastened rigidly to it with small spaces between the disks. This is the multiple disk (TESLA) turbine, where the working medium is accelerated in a nozzle and streaming radially in between smooth, flat, parallel disks which form the turbine rotor. Expanded steam is streaming out along the turbine shaft. Fig. 5 shows design principal of multiple disk turbine.

- The multiple disk turbine was patented by Nikola Tesla in 1913 [3], [4].
- This turbine is a one stage radial type expansion equipment.
- Two main parts are the nozzle and the rotor.
- In the nozzle happens the acceleration of the medium.
- The medium leaving the nozzle ingresses into the rotor, which is built up from smooth disks installed with a certain gap between each.

The simple construction of the rotor ensures that the turbine is tolerant to pollution, and has relatively low manufacturing costs. The efficiency of the turbine is not too high, it is about 30-40% at nominal load (depending on the parameters of the working medium). To limit efficiency is advantageous from the point of steam humidity. When inlet steam is saturated, outlet steam will contain only a small amount of humidity. The turbine contains a nozzle which accelerates the working medium and leads it to the rotor in the appropriate direction. The turbine construction ensures that nozzles can be replaced with another one, varying its cross section, or variable nozzle may be applied. This ensures a flexible adjustment to different pressure and mass flow rate demands. Nominal mass flow rate can be adjusted to actual demand (in a certain range). A further advantage of application of this system compared to other type of expansion equipment facilities is that it does not need further purification of boiler feed-water. Normal feed-water quality, which is adequate for e.g. shell type boiler is adequate for this system.

A system has been developed according to above mentioned conditions. A side view and the functional connection of the system can be seen in the Fig. 6.

In a further step we have analyzed economical application conditions of this system in case of different nominal power and different utilization factor. Investigation is based on existing heat supply system, where steam-pressure has been reduced by throttling. It was investigated advantages of the installation

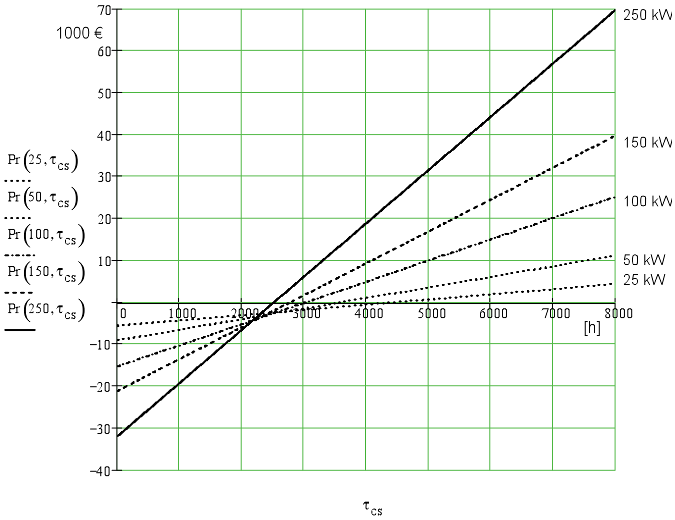

Figure 7. Profit variation at different power rate and in case of different utilization hours [2]

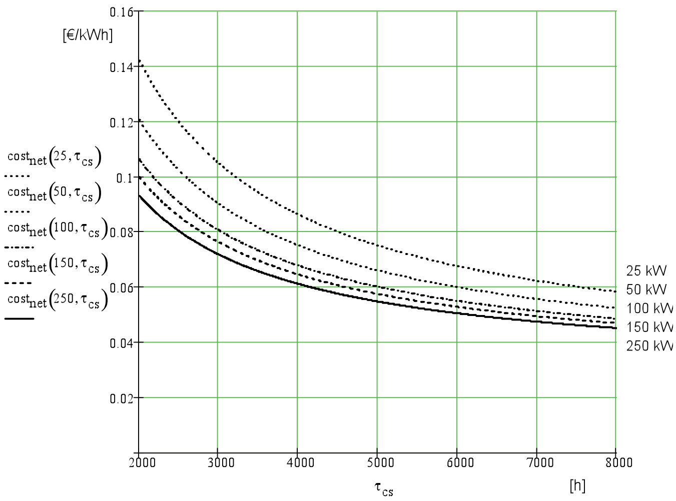

Figure 8. Net cost variation of electricity generation from pressure reduction with application of our system at different power rate and in case of different utilization hours [2]

of pressure reducer turbine instead of throttling valve. Costs are categorized to constant and proportional part. Constant cost is given mainly by installation and maintenance cost. Proportional is given mainly by extra fuel cost. Income is calculated according to the average price of electricity. Results of this analysis can be seen on Fig. 7 and on Fig. 8 for different nominal power level as the function of utilization hours.

Summary

Significant expansion of utilisation of co-generation may be achieved with implication of small- and medium scale heat supply systems. Multiple-disk turbine may be the expansion equipment which is suitable for realisation of co-generation in small- and medium scale steam supply systems. Since the plain construction it can be produced at reasonable price, so co-generation can be economical even at low power rate. The turbine can be installed instead of throttling valves into existing steam generation systems without significant modification. In this way scope of co-generation method may be expanded significantly, which helps energy saving and reduction of CO_2 emission.

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