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Electricity from industrial waste heat using high-speed organic Rankine cycle (ORC)

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Abstract

In the conversion of low temperature heat into electricity the greatest efficiency is obtained in many cases by using an organic Rankine cycle (ORC). The ORC-process may be feasible also in high temperature applications, if the output is small. This paper deals with an ORC-design, in which a high-speed oil free turbogenerator-feed pump is used. The use of high-speed turbogenerator makes the ORC small, simple, hermetic and reduces significantly the maintenance expenses.

Keywords: Organic Rankine cycle; Electricity production

1. Introduction

In the conversion of low temperature heat into electricity the greatest efficiency is obtained by using a Rankine cycle. A typical low temperature heat source is the waste heat in combustion engines and in industrial processes: hot gases from blast furnaces in the steel industry and from kilns in the ceramics industry, exhaust gases of diesel engines and gas turbines, hot liquids used to cool kilns or furnaces, etc.

Organic Rankine cycle (ORC) is a Rankine cycle, where an organic fluid is used instead of water as the working fluid. Particularly in low temperature applications many benefits may be obtained by using ORC instead of steam Rankine process.

Many commercial and test plants are made by using organic Rankine cycle. It is estimated that there are about 30 commercial ORC plants built before 1984 with an output over 100 kW. The most common fluids used are refrigerants R11 (CCl_3F), R113 ($C_2Cl_3F_3$), R114 ($C_2Cl_2F_4$), toluene ($C_6H_5CH_3$) and fluorinol (CF_3CH_2OH), or fluorinol mixed with water. The ORC-plant in general is treated in [1, 2].

2. ORC-process compared to steam process

When the heat source is waste heat at a moderate inlet temperature, the best efficiency and highest power output is usually obtained by using a suitable organic fluid instead of water in the Rankine cycle. This is mainly because the specific vaporization heat of organic fluids is much lower than that of water. Thus the organic working fluid "follows" better the heat source fluid to be cooled [3].

An example of this is shown in Fig. 1, where the heat source is the exhaust gas of a gas turbine. In the ORC-process the exhaust gas can be cooled to a significantly lower temperature. This means, that more electric power can be produced from a given heat source.

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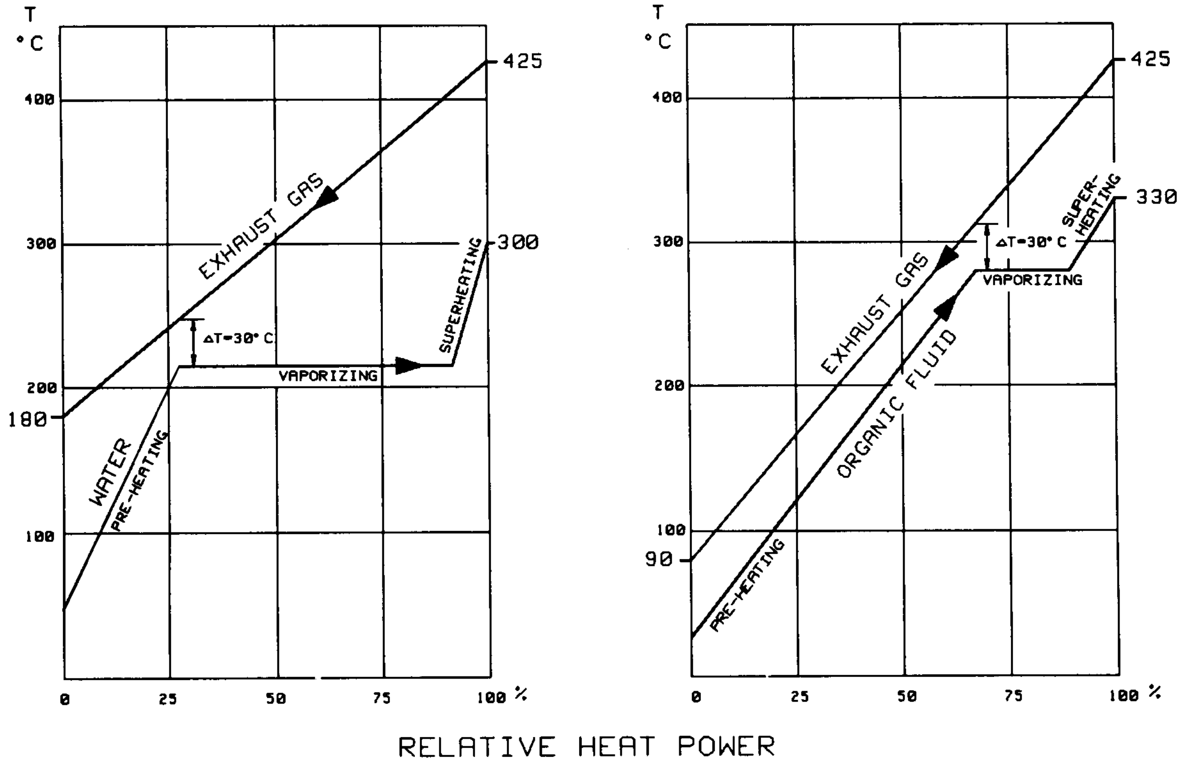

Fig. 1. The specific heat of vaporization of organic fluids is much lower than that of water. Thus the organic working fluid "follows" better the heat source fluid to be cooled (in this example exhaust gas of a gas turbine).

Also, the typically low drop of specific enthalpy in turbines with organic fluids makes the turbine design easy. In most cases a single stage turbine may be used instead of a multi-stage turbine, as required for steam. Specially, when the output of a plant is below 1–2 MW, significantly higher output and simpler design is usually achieved by using an organic fluid instead of water.

For example, in the case of Fig. 1, drop of specific enthalpy in turbine is 614 kJ/kg in steam process and 188 kJ/kg in ORC. As a result of this, the total efficiency of a single stage 500 kW turbogenerator is 38% for steam and 70% for ORC (toluene as working fluid). These values are for new commercial units.

Thus the total efficiency of ORC is in many heat recovery applications twice as high than that of steam-process, if the output of the unit is moderate. In majority of the industrial waste heat applications the available electric output of a single heat source is below 1 MW.

3. Principle of high-speed technology

To be economically feasible and viable, the ORC-plant should have a low price and, because of its small power, it should require only minimal maintenance.

In the conventional ORC-solution, an axial turbine drives a standard generator through a high-speed gearbox. The system includes a separate feed pump, vacuum pump, lubrication system and requires several shaft seals, see Fig. 5. The seals of the turbine have a limited working life in particular due to the high speed required. Thus, the entire present conventional ORC-plant is rather complicated and requires maintenance.

Because of these problems, a project was started at the beginning of 1981 at the Lappeenranta University of Technology to develop a high-speed, process fluid lubricated turbo-generator-feed pump as the prime mover of the ORC.

In this system, the turbomachines (turbine and pump) and electric machine (generator) are always directly coupled; that is, no gear box is used. The fundamental idea is that for each process there is a power and an angular velocity to give simultaneously high efficiency both for the turbomachine and for the electric machine. This maximum-efficiency speed is inversely proportional to the square root of the power, and for each process and for each design it is possible to find an optimum power which gives the minimum weight/power ratio of the energy converter.

Thus, the optimum solution aimed at is an energy converter with minimum weight/power ratio which also operates at maximum efficiency. For example, in the case of an ORC-plant [4, 1] the minimum of weight/power ratio of turbogenerator is found to be $m/P_e = 3\ \mathrm{kg/kW_e}$ with $P_e = 100\ \mathrm{kW}$ and $\omega = 3140\ \mathrm{rad/s}$. At power $P_e = 3300\ \mathrm{kW}$ and speed $\omega = 377\ \mathrm{rad/s}$ (60 rev/s) the weight power is as high as $10\ \mathrm{kg/kW_e}$ with similar design. On the other hand, at very high speed $\omega = 15\,700\ \mathrm{rad/s}$ the weight/power ratio is increased to $6\ \mathrm{kg/kW_e}$ from the above mentioned minimum.

Thus, for each process and design it is possible to find a minimum of the weight/power ratio, Fig. 2. When rotor speed increases, the weight/power ratio of rotor decreases. However, at high speeds, the weight/power ratio of generator stator and turbogenerator body starts to increase, if the design is kept cost-efficient. So, the exact value of the minimum weight/power ratio and the corresponding speed depends on the design and the choice of materials (in this example, the body was made of steel; the use of aluminum would reduce the weight significantly).

For mass production, the specific price is nearly proportional to the specific weight. Thus high-speed technology makes it possible to achieve lower investment costs by producing the required power with several parallel, high-speed technology energy converters instead of one single unit, Fig. 3. The minimum of specific cost is however obtained at lower speed and higher output per unit than the minimum of weight/power ratio (Fig. 4). Therefore the optimum size of an ORC turbogenerator is higher and speed lower than in the example of Fig. 2.

The generality of the principle that the specific cost and weight/power ratio are reduced by increasing speed can be demonstrated with diesel engines, Fig. 4. It can be seen from Fig. 4, that a small, high-speed diesel engine has a much lower specific cost and weight/power ratio than a large, low-speed engine. However, the required power produced with small diesel engines means more cylinders and a lot of maintenance. Therefore it is not economically feasible to construct a diesel power plant with, say a hundred small diesel

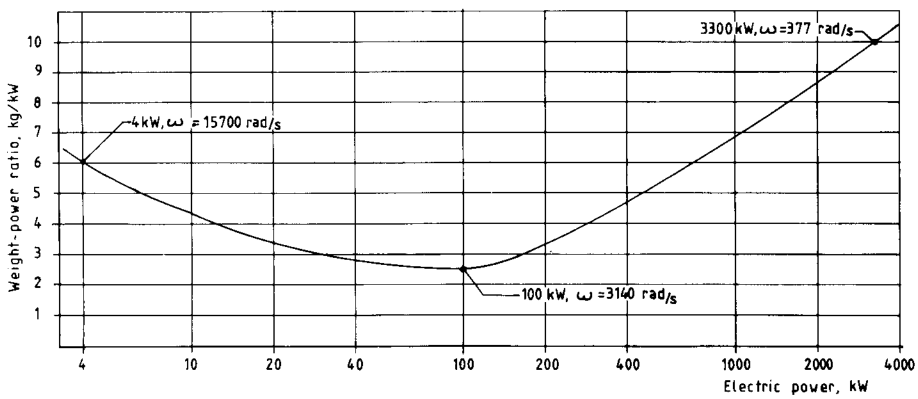

Fig. 2. Weight/power ratio of the turbogenerator-feed pump of ORC-power plant as a function of electric power; one possible design.

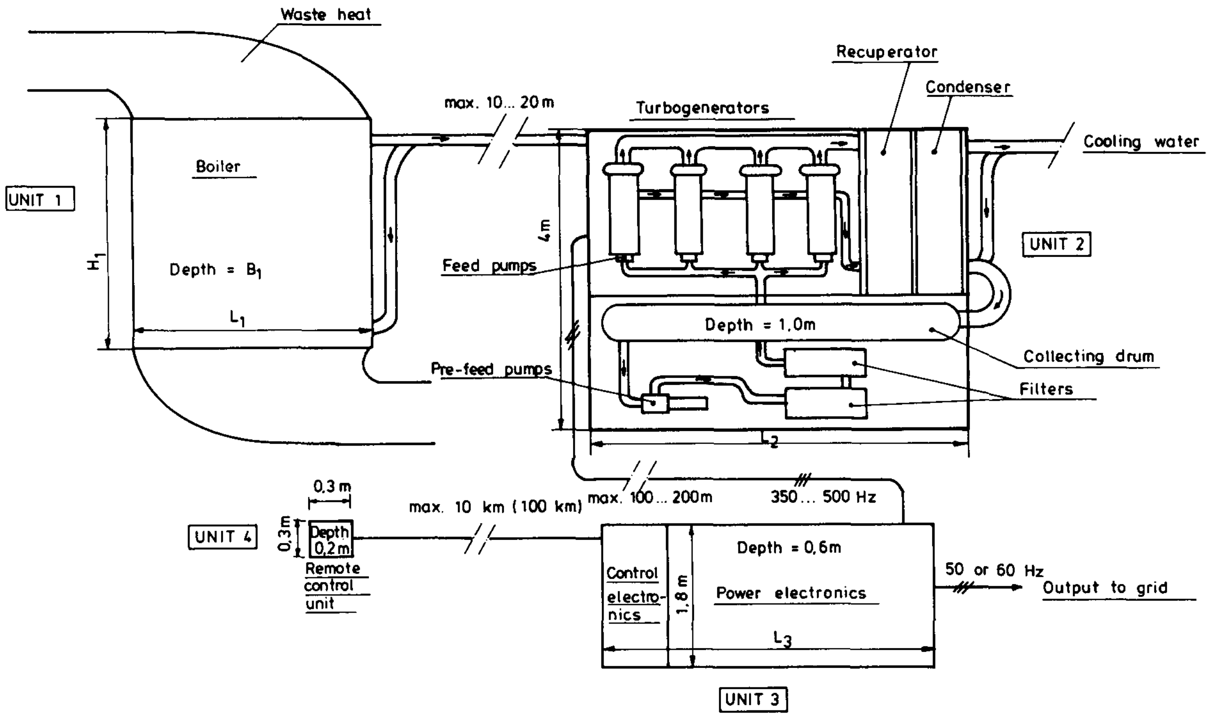

Fig. 3. Larger ORC-plants of new technology are achieved with several (in this example four) parallel turbogenerator units, but with a common boiler, recuperator, condenser, collecting drum and electric system.

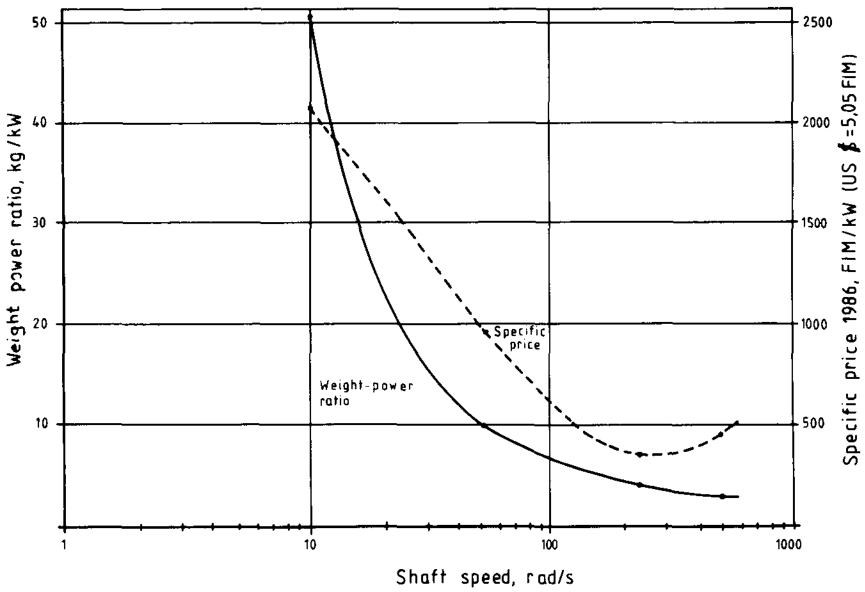

Fig. 4. Weight/power ratio and specific price of some diesel engines as a function of shaft speed.

engines, even though the specific investment cost would be low.

For this reason it is essential for the high-speed energy converter to be virtually maintenance-free and this is possible if process fluid lubrication, labyrinth seals and pure circulation fluids are used.

Fig. 5 shows a comparison between conventional technology and high-speed technology for the energy converter of a 100 kW_e ORC. The generator of conventional solution (A) produces standard 50 Hz current and the generator of high-speed solution (B) produces 500 Hz current, which is electronically converted to stabilized 50 Hz current. The high-speed solution is oil-free (process fluid lubrication) and hermetic (no shaft outlets). It should be noted, that it is not possible to lubricate a gear box with process fluid because of the low viscosity of typical fluids.

Because the turbine must rotate at high speed in order to obtain an acceptable efficiency, making a tight shaft seal is difficult, particularly if the process is kept oil-free. The conventional solution therefore has an oil circuit, and there is usually some leakage through the shaft seals [1]. In the high-speed solution it is possible to let the turbine and the feed pump rotate at about optimum specific speed. The component efficiencies obtained are high despite the small output (e.g. efficiency = 80–85% with a 130 kW turbine), and because of the hermetic, process fluid lubricated design of high-speed ORC, the maintenance costs are very low also in plants with many parallel turbogenerators.

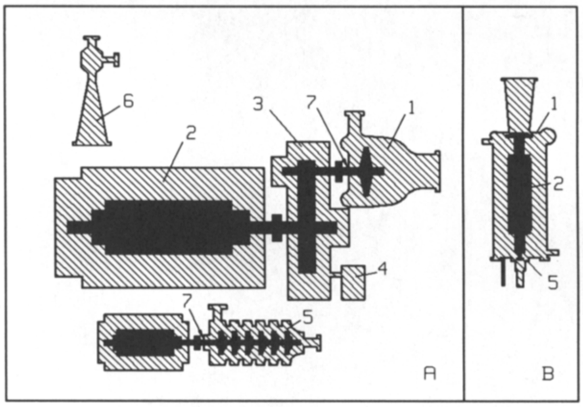

Fig. 5. Comparison of ORC-power plant of 100 kW_e realized (A) with conventional technology and (B) with high-speed technology (same scale). 1 turbine, 2 generator, 3 reduction gear, 4 oil pump, 5 feed pump, 6 vacuum pump, 7 shaft seal.

More details about high-speed technology are presented in [5].

4. Design of an ORC-plant with high-speed technology

4.1. Selection of fluid

Properties of several organic fluids were analyzed, and R114 ($C_2Cl_2F_4$) was first selected as most suitable. It is non-flammable, non-toxic, creates an overpressure to the condenser, gives good process efficiency, has satisfactory thermal stability and enables the use of a low-cost, single stage turbine. It should be noted that the complete lack of oil (due to high-speed technology) significantly improves the thermal stability of R114.

R114 was used with good results in the first two prototypes built and tested during 1983–1989. However, because R114 is a CFC-compound, it is necessary to find alternatives. Because the process is hermetic, there is no real danger for the ozone layer, but by using a CFC-compound it is difficult to fulfil the international requirements.

Therefore other fluids, fluorinol-85 and toluene, were tested for the third prototype built in 1989–1990. Finally, toluene ($C_6H_5CH_3$) was selected as the most suitable at least, for high-temperature process, Fig. 1. Its rate of thermal decomposition in oil-free conditions is very low up to about 400°C.

For low-temperature applications, isobutane (C_4H_{10}) is found to be quite suitable. In such conditions it follows better than toluene the fluid to be cooled.

4.2. Turbogenerator

The optimum size of the turbogenerator-feed pump to be manufactured in series is found to be 250 kW_e. Corresponding shaft speed is 2512 rad/s.

For prototypes $P = 70\text{–}100\ \mathrm{kW_e}$ was selected as the output of a single turbogenerator and $\omega = 2800\text{–}3140$ rad/s as the nominal speed, which gives $m/P \approx 3\ \mathrm{kg/kW_e}$.

It should be noted, that the total output of the plant depends on the number of parallel turbogenerator units, Fig. 3. A practical upper limit is about $5000\ \mathrm{kW_e}$ with a single boiler-condenser system.

For isobutane and R114 the most suitable turbine type is a single stage, inward flow radial turbine. It is used in the first and second prototype. In case of toluene, a supersonic axial turbine is more suitable due to the high-pressure ratio. It is used in the third prototype. The feed pump is a single stage, kinetic pump with contact-free labyrinth seals.

As generator, both asynchronous and synchronous types are tested with good results. Small size, high-speed and high-power density set special requirements for the design. The supply of magnetization current to a generator stator may be made either by capacitors regulated by magnetic amplifiers (first prototype), or by using an inverter (second prototype). In case of synchronous, permanent magnet rotor no external magnetization is required (third prototype).

Fig. 6. shows the turbine-generator-feed pump rotor of the first turbogenerator. It is economical to keep the rotor subcritical for bending to avoid the complex balancing of a supercritical rotor.

4.3. Bearings of the turbogenerator rotor

It is advantageous to install the rotor of high-speed turbogenerator vertically. This offers the minimum starting load to radial bearings and the starting load of thrust bearing is easy to compensate by suitable pressure distribution. In oil free operation we have three basic alternatives: hydrodynamic bearings lubricated by the process fluid in liquid state, gas bearings lubricated by process fluid vapor and dynamic magnetic bearings.

Gas bearings of the tilting pad type were first considered most suitable and used in the first prototype and in the first turbogenerator of the second prototype. However, because of certain difficulties, tilting pad bearings lubricated with liquid process fluid were selected for the second turbogenerator of the second prototype. Because the test results were good, this type was selected also for the third prototype.

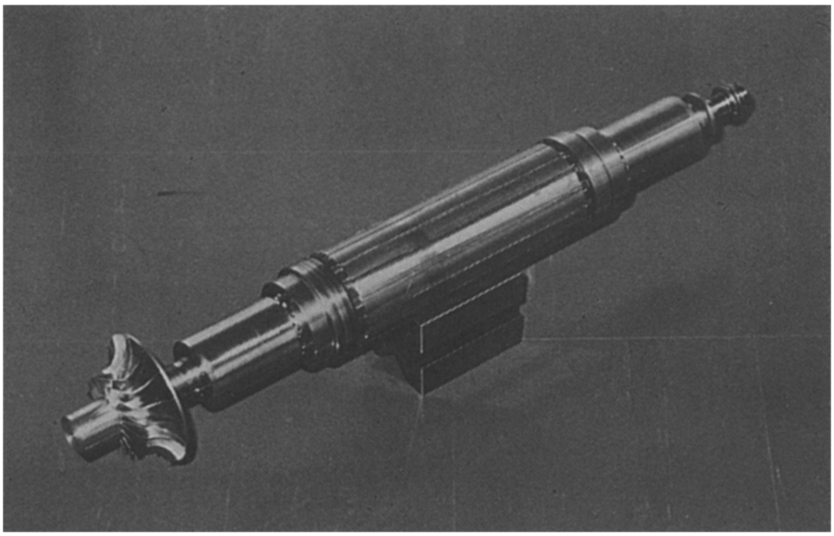

Fig. 6. The rotor of the first prototype of the high-speed, process fluid lubricated turbogenerator-feed pump. From left to right: turbine rotor, generator rotor and feed pump rotor. Electric output 100 $\mathrm{kW_e}$ at design conditions.

4.4. Circulation process

Fig. 3 shows the principle of the system. Waste heat (for example, exhaust gases) is led to a boiler where it vaporizes the working fluid. After expansion in the turbine, the vapor is converted to a liquid by means of a condenser.

The liquid is returned to the boiler with a single stage high-speed pump through a recuperator. As mentioned previously, the basic idea is that the turbine, the generator and the feed pump have a common process fluid lubricated rotor. The entire system can be hermetically enclosed since there are no shaft outlets. The pump and the turbine have wear-free labyrinth seals and leakage, being possible only to the turbogenerator casing, flows back to the condenser. The pre-feed pump has a motor exposed to the working fluid and working fluid lubrication.

This hermetically enclosed design requires no vacuum pump and process fluid lubrication makes an oil system unnecessary. The high frequency current produced by the generator is rectified and converter to stable current which can be fed into the electricity network. The whole ORC-plant with this new technology is quite simple, with only one moving part in the power system and because of process fluid lubrication and the lack of tight shaft seals it is expected to require very little maintenance indeed. The boiler is usually of the once-through type with finned tubes.

As mentioned previously, a high-speed turbogenerator is a standard unit for all plants and is optimized for electric output of 250 kW. Larger plants are made simply by connecting the required number of these turbogenerators to the vapor line of a common boiled, as shown in Fig. 3. Here all the turbogenerators have also a common electric system and collecting drum for liquid fluid. This solution may be compared to a diesel engine with many cylinders, and it allows the minimum specific price for the plant. Plants may have up to 10–20 turbogenerator units providing an electric output as high as 5 MW. The plant is designed with fully automatic start and operation control and is divided to four units (boiler, energy converter, electric system and remote control unit) for easy installation.

5. Test results with high-speed ORC

The validity of the basic idea was tested during 1982 with a simple 30 kW prototype of a high-speed turbogenerator-feed pump run by compressed air. The first prototype of the complete ORC power plant with this technology, design output 100 kW, was built in the laboratory, Fig. 7.

Tests with this plant were started at the end of 1983 and completed in 1986. The second prototype is a similar ORC-power plant of 100 kW_e, but installed to use a real, industrial waste heat source instead of operating in laboratory conditions as the first prototype. Tests with the second prototype were started in 1986. In this prototype two different types of turbogenerators were tested, as mentioned previously.

The third prototype was built during 1989–90, and it is in continuous operation. The first two prototypes were designed for medium temperature waste heat and the third for high-temperature waste heat.

Test results have been promising, but also many minor difficulties have appeared. The performance of the turbine and feed pump have corresponded to calculated values, but bearings, generator and inverter have required much development work. Performance of the third prototype has however

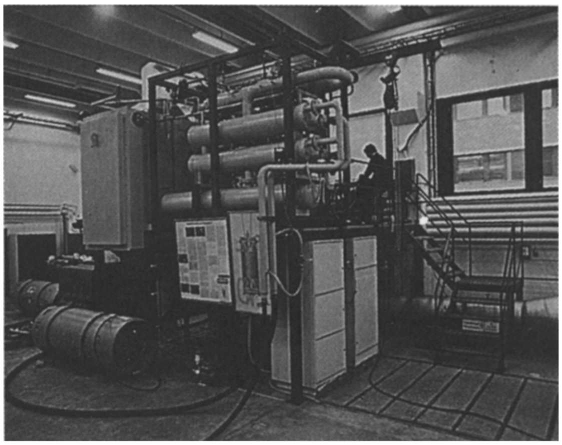

Fig. 7. The laboratory prototype of the ORC-plant based on high-speed technology.

Table 1
Basic properties of high-speed ORC for three different heat source: hot water, exhaust gas of a gas turbine and combustion gases of solid fuel. Total efficiency means, how many percent of the heat source heat content can be converted to electric power. Table includes comparison to a commercially available steam process in the case of gas turbine exhaust gases. Specific price of each case is compared to the specific price of 1500 kW steam process

Heat source	Hot liquid at 95°C	Hot gases at 425°C					Combustion gases of solid fuel
Process	HS-ORC 1000 kW (%)	HS-ORC (%)		Steam-process (%)			Multistage HS-ORC 1000 kW (%)
		500 kW	1500 kW	500 kW	500 kW	1500 kW	
Total efficiency		17	17	7	11	11	23–27
Process efficiency	6–10	26	26	11	19	19	27–32
Specific price	~ 90	95	75	140	170	100	~ 80

been quite good, and thus an adequate technical level is considered to been reached for commercial plants. First commercial high-speed ORC plant, size 500 kW, is assumed to be built during 1995.

Numerical test results may be summarized to total plant efficiencies, which are expected in different operation conditions, Table 1.

If the inlet temperature of waste heat is very high, say 600–700°C, it seems possible to obtain as high net efficiency as 32% by using a more complex process. This kind of plant may be used to produce electric power from burning of solid, domestic fuel, e.g. wood chips. Its estimated properties are also shown in Table 1.

6. Applications and summary

Basic application of the high-speed ORC-plant is the production of electric power from waste heat of industrial processes and combustion engines. Some typical waste heat sources are listed below, and additional data is given e.g. in [1, 3, 6–8]. Typical industrial waste heat sources are:

- hot gases from blast furnaces in steel industry,
- exhaust gases of gas turbines and diesel engines,
- hot gases from kilns in ceramic industry,
- thermo oil or other hot liquid used to cool kilns in building material industry,
- hot liquids in paper and pulp industry.

Basic idea is of course, that this thermal energy cannot be used efficiently in the process or in district heating. Thus it may be called waste heat, and will have value only, if it can be converted to electric power. The amount of this kind of waste heat in the whole world is enormous.

There are also several other applications, for which the hermetic high-speed ORC may be very suitable: the production of electric power from solid fuel for remote villages in developing countries, geothermal power plants, and acting as additional [8] or as the primary energy source for vehicles.

By using high-speed technology in ORC-plant several benefits are obtained compared to the conventional turbine-gearbox-synchronous generator solution:

- light weight and small size; easy to assemble,
- long technical lifetime and small service costs,
- small outputs possible with good efficiency,
- hermetic design; no process fluid leakage,
- significantly higher thermal stability of the process fluid because of oil-free operation.

The competitiveness of the units manufactured commercially should also be significantly better than with conventional technology. The numerous units with small high-speed generators used in telecommunication stations [9] have verified the reliability of high-speed technology in practice.

In Table 1 there are summarized the basic properties of high-speed ORC according to measurements and calculations. Some comparisons to the water steam process of one manufacturer are also included.

Three complete prototypes of the high-speed ORC have been made; two for medium temperature waste heat using R114 as working fluid and one for high-temperature waste heat using toluene as working fluid. Now, when the tests with the third prototype are finished, it is considered that an adequate technical level is reached to deliver customer-ordered plants. The first really commercial high-speed ORC-plant is assumed to be built during 1995. The manufacturer of the plants will be the High-Speed Technology Ltd.

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