The Tri-O-Gen Organic Rankine Cycle:

development and perspectives

by
J.P. van Buijtenen
Tri-O-Gen B.V.,
Goor/Delft University of Technology,
The Netherlands

Abstract

The principle of the ORC (Organic Rankine Cycle) is well known already for decades. However, most of the present ORC-plants are based on conventional turbine technology, which includes shaft seals, a reduction gear and a lubricating oil system. A new turbo-generator concept has been developed, using Toluene as a working fluid and lubricant. This concept allows a completely hermetic design, with no need for shaft seals or a separate lubrication system. Toluene is a combustible solvent, but it has high thermal stability and is not marked as poisonous.

The ORC process demands a very high expansion ratio, at moderate turbine inlet temperature. A standard 175 kW (gross power) unit is able to run at optimum specific speed for turbine and pump on the same shaft as the high-speed generator.

This paper will describe the novel turbo-generator as well as the total packaged system, as it recently has been introduced on the market.

Introduction

Many attempts have been made to design small scale Rankine Cycles, using both water and steam as other (organic) working fluids. The main problem is to match small turbomachinery, which prefers to run at high speed, with generators which until now had to run at maximum 3000 rpm. The advent of high-speed generators enables the design of micro gas turbines, as well as turbo-machinery for two-phase thermodynamic processes.

ORC (Organic Rankine Cycle) is a Rankine cycle that uses an organic fluid as the working fluid instead of water/steam. The main idea in most of the ORC-plants is to produce electric power from relatively low temperature heat and or relatively small amounts of waste heat. For low temperature waste heat applications ORC provides many benefits compared with the steam Rankine process. Typical low temperature heat sources for ORC application are the waste heat from combustion engines, gas turbines, and many industrial processes.

A new turbo-generator concept has been developed, using Toluene as a working fluid, which as a liquid can also be used for lubrication of conventional tilting pad and tapered land bearings. This concept allows for a completely hermetic design, with no need for shaft seals or a separate lubrication system.

The Organic Rankine Cycle process demands a very high expansion ratio, at moderate turbine inlet temperature. A standard 175 kW unit is able to run at optimum specific speed for turbine and pump on the same shaft as the high-speed generator.

The design procedure started with the design of the cycle process including the selection of appropriate process parameters for the assumed operating conditions. Turbine and pump were designed based on the calculations of the ORC process.

ORC with high-speed technology

For heat sources (e.g. flue gas) at a moderate temperature a suitable organic fluid is usually used in the Rankine cycle, instead of water, in order to obtain the best efficiency and the highest power output. Also, the boiler construction and turbine design is much easier than for a steam power plant. Using a suitable organic fluid typically provides a low drop of specific enthalpy in turbines, which makes a high efficiency turbine design possible. In most cases a single-stage turbine may be used.

The ORC with high-speed technology is completely hermetic and oil-free, and the liquid working fluid is used for lubrication of the bearings of the high-speed turbo-generator. In this system, the high-speed turbine, generator, and feed pump are directly coupled on the same shaft (Fig. 1). The inverter between the generator and the electrical network converts the high frequency current to the frequency of the grid (50 Hz or 60 Hz).

In this research an ORC-plant using toluene as the working fluid has been developed. The main feed pump feeds toluene to the boiler, where it is preheated, vaporized, and superheated. The superheated vapour expands in the turbine that runs the high-speed generator and the main feed pump. It is specific for toluene that the vapour gets more superheated (i.e. contains more sensible heat) when it expands in the turbine (Fig. 2). The superheated vapour is cooled in the recuperator and condensed back to the liquid state in the condenser. The recuperator is used for preheating the liquid toluene that is fed to the boiler. The pre-feed pump is used to maintain sufficient pressure for the main feed pump and for the bearings of the high-speed turbogenerator.

Process values used in turbine design are:

- Generator power 175 kW
- Vapour temperature at turbine inlet 325°C
- Turbine inlet pressure 32 bar
- Turbine outlet pressure 0,27 bar
- Mass flow rate of working fluid in turbine 1.25 kg/s

After designing the process components (heat exchangers, pumps, etc.) off-design calculations were made to estimate the performance of the ORC in assumed operating conditions. The net electric efficiency indicates that in these assumed conditions about 22% of the boiler heat rate can be converted into net electric power if external cooling water is available and air coolers are not needed. The net electric efficiency is about 20% if air coolers are used.

Selection of working fluid

The selection of the working fluid has to be made on the basis of a number of conditions:

Thermodynamic:

- Critical pressure and temperature
- Shape of the Mollier diagram
- Pressure/temperature at condensation

Environmental Effects:

- If released into the atmosphere
- After combustion

Safety Aspects:

- Toxicity
- Inflammability

Operational:

- Chemical stability at high temperature
- Effects on lub-oil
- Electrical conductivity
- Lubricating properties

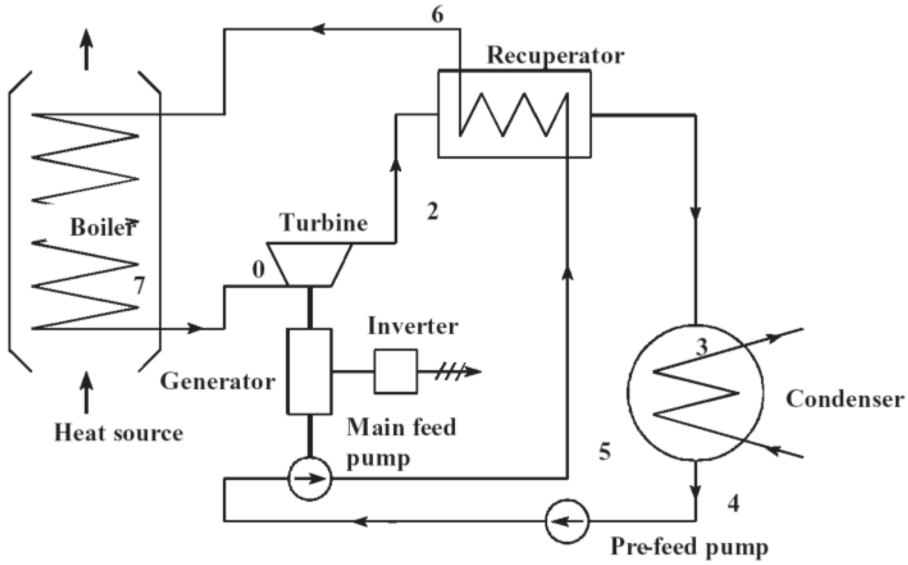

Fig 1 Schematic flow diagram of ORC (simplified)

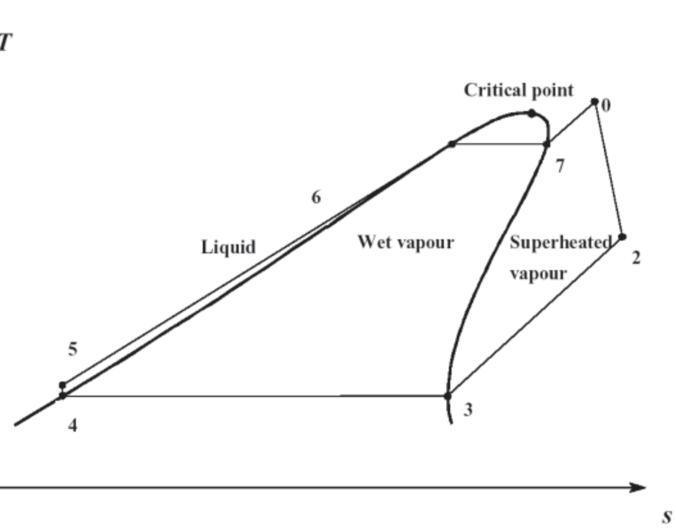

Fig 2 Principle of ORC process on T,s-diagram (simplified, not to scale)

Various researchers and industries favour various working fluids. In the table below an overview is given:

	Toluene	n-pentane	Siloxane	R245fa	Water/steam
Critical temperature [°C]	321	196	292	155	374
Critical pressure [bar]	42	34	14.4	37	221
Self-ignition temperature [°C]	480	309	482	?	-

Tri-O-Gen selected toluene. The first reason is the high chemical stability at temperatures well over the level of most waste heat source temperatures. This allows the system to operate at a the relatively high temperature of the exhaust gases of gas engines and gas turbines, even allowing for the use of flue gases from direct combustion of wood or waste gases. The second reason is the fact that liquid toluene can be used to lubricate the bearings of the turbogenerator, while at the same time the vapour takes care of cooling of the electrical parts of the generator, because of the electric conductivity being virtually zero. From a health and environmental viewpoint, toluene can be well accepted, comparable to transportation fuels like gasoline and many solvents used in the printing industry. There is no indication of any carcinogenic effect, while in the event of a fire the pure hydrocarbon will only produce water and carbon dioxide. As the system is inherently hermetic, leaks are very unlikely. If such leak should occur, alarms are set at 50 ppm concentration, and at 100 ppm concentration, the unit will shut down. As a comparison: the lower explosion limit of toluene in air is 12000 ppm. Most regulatory bodies accept incidental emission of toluene into the atmosphere.

The high allowable working fluid temperature is favourable for high Carnot efficiency and high temperature differences in all heat exchangers. The high thermal efficiency exploits the available waste heat to its maximum, while heating surfaces remain moderate. The result is a compact and economically viable total plant.

Test assembly for the complete ORC plant

The high speed ORC plant is built to a standard container, Fig. 3. The process itself is fully hermetic and the amount of working fluid (toluene) is c. 300 litres.

This initial prototype was built in Finland, under the guidance of Prof. J. Larjola of the Lappeenranta University of Technology, and the designer of the turbo-generator. The philosophy was to build a unit within the main dimensions of a standard sea-container. The container was divided into three compartments:

- The evaporator (most front)
- The process compartment, containing turbo-generator, recuperator, condenser and all ancillaries necessary to run the plant
- The electrical compartment, containing the frequency converter, the PLC controller and the switchgear to govern all components

The main process components are stacked in a vertical way: on top there is the turbogenerator with the shaft in a vertical position. The outlet of the single stage turbine rotor is facing downwards to the recuperator, below which the condenser is situated. Both heat exchangers are of the compact plate type. There is a container below the condenser to store sufficient inventory of liquid working fluid.

If no cooling water is available, the condenser heat is taken by external air coolers to reject the heat of the condenser cooling water. In this case, the air coolers are placed on the roof of the container.

After two years of development at Tri-O-Gen in The Netherlands, the unit was put on a landfill site for endurance testing, making use of otherwise flared landfill gas. Fig. 4 shows the location.

This first Tri-O-Gen ORC operated more than 10.000 hours and more than 500 cycles. The longest uninterrupted run lasted over 3 months. Interruptions were mostly caused by a lack of landfill gas produced, or lack of methane content. The residual heat from the condenser was used for pre-heating a waste water tank to stimulate the digestion process.

HTG: High speed turbogenerator

Thanks to the use of the high speed generator (20.000 - 28.000 rpm) and the directly coupled single stage radial turbine wheel and main feed pump, the turbo-generator is a very compact and easily replaceable unit. The height and diameter amounts to 80 cm, and the weight is less than 500 kg. Fig. 5 shows from left to right the turbine stator and

Fig 5 Stator nozzle ring (one half), turbine rotor, generator rotor, cooling fan, pump impeller

Fig 3 High speed ORC power plant container on the test site

Fig 4 First Tri-O-Gen ORC at long term test location "Stainkoeln", Groningen

rotor, the generator rotating body, the cooling fan which takes care of flow of toluene vapour for cooling and the rotor of the main feed pump. This whole rotating assembly is placed in a casing, which has only flanged connections to the other process components. Doing so, there is no need for shaft seals and a gearbox. The bearings are lubricated by the working fluid, so no mixing can take place with lubricating oil (nor subsequent separation of both).

In turbo-machinery design, it is well known that for optimum efficiency there is a clear relationship between stage loading and through-flow on the one side and speed and diameter on the other. For such small flow, considering the envisaged power, flow channels must be small, while peripheral speed is determined by the specific enthalpy drop necessary for high system efficiency. This means that for this low power a small diameter had to be chosen, while maintaining peripheral speed, meaning a high number of revolutions per minute. So when using a conventional 3000 rpm generator, the turbine either has a very large diameter (much larger than optimal for this power level, so at a cost in efficiency), or an expensive gearbox should be used. Such a gearbox not only requires initial investment, but also power losses, maintenance and lubricating oil. The chosen combination is considered as optimal for turbine, generator and pump efficiency..

The high speed generator runs independent of grid frequency. The speed is governed by the ORC PLC controller, by setting a speed through the frequency converter. The power electronics take care of constant frequency and voltage delivery to the grid, irrespective of turbo-generator speed. This allows for smooth start-up and stopping, while maintaining a high efficiency also at part-load condition.

Fig 6 Turbo-generator as assembled to the ORC power plant

The Tri-O-Gen ORC

After successful testing of the prototype, both for performance and life, the lessons learned were applied in the commercial version. The first unit was sold to a greenhouse owner, who operates a 2 MWe gas engine for power and heat supply to his greenhouse, where roses are being grown. The unit was put into operation early 2008, and has gathered

Fig 7 First commercial Tri-O-Gen ORC plant

more than 4000 hours. The plant is started every morning at 07.00, and shut down at 20.00 hours. Gross power amounts 140 kWe, depending on the gas engine power setting. Fig. 7 shows the plant.

In this new design a modular concept has been adopted. Process room and boiler are still assembled on one transportable skid, leaving room for varying boiler dimensions depending on the application and heat source properties. The process part is standardized and will be fully factory assembled together with the boiler. The electrical room is separated, and can be integrated with similar equipment at the customer's site.

Applications

A wide variety of (waste) heat sources can be used to operate the Tri-O-Gen ORC. For the envisaged 150 kWe net power, the heat source must be at least 400°C, while the amount of heat to be transferred to the working fluid must be 760 kW. Exhaust gas temperature will then be over 180°C. This heat, together with 620 kW at low temperature coming from the condenser might be used in low temperature applications, as space heating or process heating in digesters. Fig. 8 sumarises this data.

The applications can be divided into two categories, depending on the origin of the heat:

1. waste heat from existing processes or prime movers
2. heat coming from the combustion of fuels which do not meet the specifications of internal combustion engines or gas turbines

In the first category the following applications will be possible:

- exhaust heat from gas and diesel engines (engine power > 1500 kW)
- exhaust gas from small gas turbines (gas turbine power > 400 kW)
- industrial processes:
  - steel and aluminium production
  - glass production
  - brick ovens
  - food and dairy industry

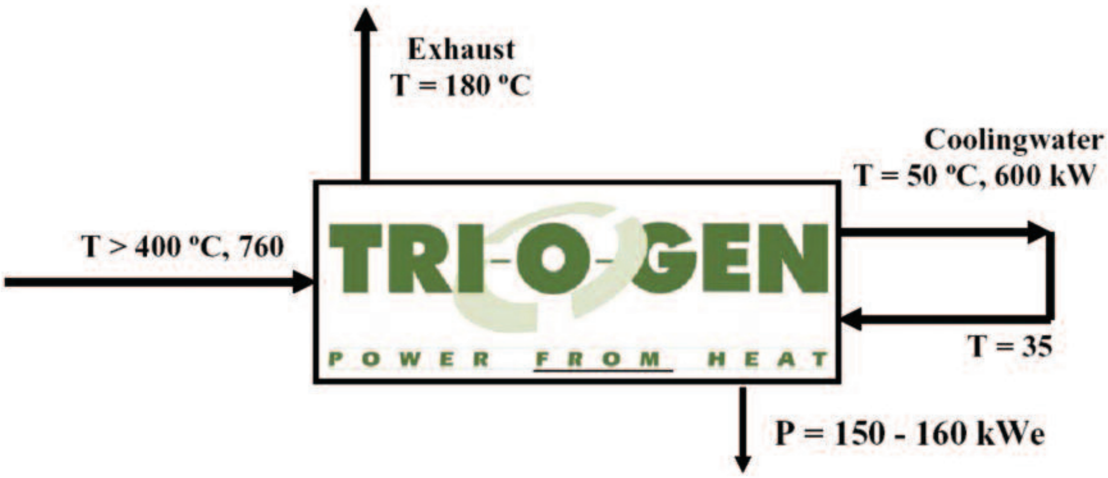

Fig 8 Energy balance for the Tri-O-Gen ORC

The second category requires combustion equipment for fuels and waste combustible substances, which cannot be used in internal combustion engines. Examples are:

- solid biomass like wood
- flare gas
- landfill gas

In co-generation plants, the ORC can add to the flexibility to use the heat either for heating or the production of extra electricity, depending on the actual heat demand.

Conclusions

A new Organic Rankine Cycle concept has been developed and optimised, taking into account the special boundary conditions and opportunities given by the working fluid and the high-speed generator. With this concept the next step can be taken towards the application of high-efficiency small turbo-machinery, following the recent introduction of micro-gas turbines. The Tri-O-Gen Organic Rankine Cycle system will find a variety of applications:

- as bottoming cycles for diesel and gas engines and gas turbines
- for the utilisation of industrial waste heat
- for the use of waste and bio-mass fuels which are unsuitable for combustion in internal combustion engines.

Detailed tests of the whole plant proved to be successful, and commercial application has been started. After initial application in The Netherlands, export will start in due time. ■

References

Prof. ir. Jos van Buijtenen, Prof. J. Larjola et al: *Design and Validation of a New High Expansion Ratio Radial Turbine for ORC Application*, 5th European Conference on Turbomachinery, Praag, March 2003

J. Heinimo, J.P. van Buijtenen, J. Larjola, J. Backman. *Small Electricity Production with High Speed ORC Technology*. International Nordic Bioenergy 2003 Conference, Jyvaskyla, 2/5 September 2003

Heinimö, J., van Buijtenen, J.P., Backman, J., Ojaniemi, A. & Malinen, H.: *High-Soeed ORC Technology for Distributed Electricity Production*, 2nd World Conference on Biomass for Energy, Industry and Climate Protection, 10-14 May 2004, Rome, Italy.

Questions and Answers

Q Is the design of the turbine special and unique, or is its design based on a 'commercial-off-the-shelf' unit which has been customised? Also, where does the 'intellectual property of Tri-O-Gen lie; is it in the specialised Rankine Cycle system, or the turbine design, or the control protocols?
John Kitchenman, Retired

A The design of the turbine, or better the 'High speed Turbo-Generator' referred to as HTG, consisting of single stage turbine, high speed a-synchronous generator and main feed pump, all on one shaft, is a specially developed unit for this application. The majority of the development work has been spent on this unit. The Tri-O-Gen IP is by consequence concentrated in this HTG, but on the level of ORC system and control we have found some unique solutions to fully exploit the possibilities of this Organic Rankine Cycle.

Q What are the benefits over using an HRSG?
PB Power

A I expect that by HRSG is meant: conventional steam cycle. In comparison with a steam cycle the advantages of ORC can be found in: a) the maximum temperature of the working fluid that can be achieved in view of the available heat flux to be converted into electricity and b) the relative scale of the unit. Steam cycles are optimal if the steam can be superheated to ~ 550°C, and preferably twice through the application of reheat. Moreover the optimal pressure is in the order of 150 - 200 bar. The temperature of the heat sources to be applied here is generally lower, while at small scale the mentioned high pressures would lead to very small pipe diameters with unfavourable hydraulic diameters. At small size one would also prefer to refrain from complications like reheat. Using an organic fluid there is no necessity for reheat, as the shape of the wet area in the thermodynamic diagrams shows. Furthermore, a lower pressure for the evaporator can be used, while still having the evaporation taking place close to the critical point, which limits the heating surface area and allows the fluid temperature to be raised close to the maximum heat source temperature. As the unit is meant for small scale power production, the use of steam with its associated complications such as chemical control of the feed water and make-up water, it is more difficult to reach the low operating and maintenance effort that are required. Of course using something else as water, demands the unit to be leak-free. The Tri-O-Gen unit is inherently hermetic because of the HTG design. However, this HTG design could never be used for water/steam, as the working fluid also serves as lubricant and coolant for the bearings and generator. In short: the benefits of ORC over HRSG are:

1) higher efficiency,
2) compacter unit
3) lower operating and maintenance costs.

This is valid for heat sources from 350°C, and unit size up to approx 1 MWe.

Q What is net power of one unit?
PB Power

A The net power can vary from 80 to 150 kWe, depending local conditions.

Q Why use a vertical axis turbine?
PB Power

A

1) By using a vertical shaft the main bearing load is on the thrust bearing, the radial bearings are hardly loaded. The axial forces however can be tuned to a desired low level by the selection of shaft seal diameters. During operation the axial load is reduced to a just positive value, balancing the rotor weight and turbine/pump axial forces.

2) The turbine exit is in the vertical downward position to guarantee positive flow of all exiting flows from the HTG into the recuperator/condenser.

Q What is the expected unit cost/price?
PB Power

A We are now selling units between Euro 650,000 and Euro 750,000. Remember that this is a full turn-key price, including packaging, commissioning, basic connections to heat source and electricity grid, and means for condenser cooling. There are no civil works necessary, provided a stable flat foundation is available to carry the 12 tons unit, which can be installed either inside or outside. Electric synchronization to the grid is provided by the built-in frequency converter, which directly feeds into a 3-phase standard 400 V grid.

Q What is the cycle efficiency?
PB Power

A The cycle efficiency, defined as 'net power output' divided by 'net heat input to the working fluid' can range from 17 to 22 %.

Q What is the turn-down rate and part load efficiency?
PB Power

A At this moment we want to limit the lower power level to 70 kWe. For individual plants we are able to set the optimal efficiency depending on the heat source and its variation. So part load efficiency is dependent on these settings. As a rule of thumb: efficiency can remain virtually constant down to 80% load, below 80% load there will be a decrease.

Q Is heat from the cooling water utilised in greenhouse applications?
PB Power

A Yes, condenser heat can be utilised provided a low temperature heat sink is available. In the landfill gas application (demo-unit) this is the case: heat for the digestion process in a waste water cleaning tank. Some greenhouses are equipped with a low temperature heating circuit, which can be served.

Q Is there any specific reason for the turbine and alternator to be built in the vertical axis position, because the only time I can recall seeing this arrangement being selected was for specific reasons? Examples: The "Seajoule" system for installing waste heat recovery steam turbines in ships uptakes and small turbines to drive boiler fans for steam ships. The difficulty of access to a turbine, and thrust bearing loading due to the weight of the stator becomes greater, in the vertical machine.
Bill Page, Wärtsilä UK Ltd

A The main arguments have already been given above. In this design, removal and re-installation of the complete HTG is made very simple for quick change-out as a module. Thrust bearing loading is controlled by proper dimensioning of the internal shaft seals.

Q Please can we have more information about the source of the alternatives for the working fluid as shown by the Table in the paper. It was understood that the other researchers are from the UK, Italy and USA.
Ronald Hunt FIDGTE, Power + Energy Associates

A Indeed the mentioned working fluids are being applied by other ORC developers. The selection of the working fluid is as mentioned a function of the heat-source temperatures that one wants to cover. The Tri-O-Gen ORC is meant to serve waste heat at a temperature above 350°C. This can be waste heat from engine flue gas, gas turbine flue gas, waste heat from industrial, petro-chemical and metallurgical processes, or heat produced by combustibles which are not suitable to burn in internal combustion engines or turbines. Other developers have different heat sources in mind, even down to low temperature geothermal heat. For the time being, Tri-O-Gen will stick to toluene, for reasons mentioned.

Q During the discussion we have spoken about part load operation and operation of the turbine bearings. Please may we have your comments about this included with the final version of the paper.
Ronald Hunt FIDGTE, Power + Energy Associates

A The lower load limit is mainly given by the operation of the hydro-dynamically lubricated bearings, whose load capacity is a function of rotational speed.

Q With regard to the economics of the system we discussed pay back period and you have given us three years based on a free fuel and a delivered energy price of 13 cents/kWh. In our view Free Fuel seems to be an ideal situation. Please can you give your further comments on what might be the acceptable cost of fuel to keep the system economically attractive?
Ronald Hunt FIDGTE, Power + Energy Associates

A ' Free fuel' is to be read as: 'Free heat input', in other words: make use of otherwise wasted heat, which is the case if there is no local application to be found of heat inevitably generated by a certain process. The economic figures are 'rough' thumb-rule data. Tri-O-Gen can supply any applicant with exact financial data, based on all local circumstances, both technically as for local tax rules and green credits.

Q Prof van Buijtenen - firstly, thank you for presenting a most interesting paper this afternoon. You have indicated that the unit has a part load capability but have not mentioned any inlet guide vanes of bleed arrangements so could you please explain what need there is and how does the unit avoid surge?
Peter Tottman, IDGTE Director General

A There is no variable geometry at all in the system. Control takes place by varying HTG speed as a function of heat input. This very sophisticated system allows the unit to achieve high part load efficiency, and great flexibility in application and variations in heat source. As 'compression' is taken place in the liquid phase (pumps), there is no danger for surge. Suction head per pump is controlled by guarding a minimum level in the working fluid inventory vessel and a pre-set inlet pressure for the main pump.

Q Would it be possible to scale up from 175 kWe?
John Blowes, Diesel Consult Ltd

A Technically there are certainly possibilities for scale up. However, as a young company we would like to stick to the current version of the HTG. We think the current unit can serve sufficient applications to base our company growth on. The next step might be the application of multiple HTG's in one unit, to serve larger heat flows.

Q Will any form of clean-up be required when directing exhaust gases to greenhouse crops?
John Blowes, Diesel Consult Ltd

A State of the art technology used there is removal of NOx and unburned hydrocarbons catalytically, especially ethene. Many greenhouses in The Netherlands are using this technique effectively.

Q How well suited is the equipment to intermittent use, such as running through peak electricity generation periods each day?
John Blowes, Diesel Consult Ltd

A The best answer here is our experience with our first commercially sold unit to Olij Collection in De Kwakel. After 4000 operating hours and 250 cycles (the unit is started every morning and shut down every evening) inspection of the unit showed no degradation or wear at all.

Q How close to a 3 year payback on capital have existing systems been and have they relied on incentives such as ROCs?
John Blowes, Diesel Consult Ltd

A See also other question above. With respect to your question: Yes, green incentives have to be taken into account, as long as basic electricity prices are low. However, we know applications, where the value of the electricity produced is set by the price the user has to pay for buying it.

Q Payback on unit with assumptions of unit costs (total costs including buildings, equipment, connects etc), electricity prices and life time O&M costs.
Will Power, ITI-Energy Ltd

A Unit cost is given above. Electricity prices including green credits are too much depending on local circumstances to give any number here. O&M costs are relatively low. Operation is unmanned, eventually remotely monitored by Tri-O-Gen. Maintenance contracts available, to be negotiated.

Q Efficiency calculations and assumptions.
Will Power, ITI-Energy Ltd

A See above.

Q HAZOP issues of toluene leaking into a gas engine exhaust that is about 500 to 410°C.
Will Power, ITI-Energy Ltd

A Auto-ignition temperature of a toluene/air mixture within explosion limits is 480°C. Engine exhaust has a lower oxygen content than air, so auto ignition will be higher at a higher temperature. In unlikely event of a leak in an evaporator pipe, the outflowing toluene will either ignite and burn into H_2O and CO^2 (as it is a pure hydrocarbon), or will be emitted unburnt, which is allowed in incidental small quantities. Detailed HAZOP study results are available in Tri-O-Gen.

Q On the operating units what is the history of operating hours and availability of the units.
Will Power, ITI-Energy Ltd

A At this moment there are two operational units:

1) The demo-unit running on the heat of combustion of landfill gas: gathered more than 12,000 hours and more than 100 cycles, unmanned operation, remotely monitored by Tri-O-Gen. Longest uninterrupted run more than 3 months. Varying power as function of landfill gas production and quality, between 80 and 130 kWe. Highest power 150 kWe achieved. Downtime 95% based on landfill gas unavailability. Only maintenance so far: cleaning of boiler flue gas side, and replacement of two sensors and UPS battery.

2) First commercially sold unit for greenhouse: utilizes surplus of exhaust heat from 2 MWe Deutz natural gas engine. Flexibility: flue gases either led through ORC evaporator and subsequent through flue gas cooler to capture remaining heat, or in case of large heat demand: flue gases 100% used for heating greenhouse. Gathered more than 4,000 hours and more than 250 cycles, as the unit starts/stops every day. Recent inspection showed no degradation or wear.

3) There are two more units sold:

a. 'Kloosterman', ORC utilizing exhaust heat from 2 Jenbacher (835 kWe) engines running on bio-gas from corn fermentation will be commissioned during February,
b. 'Eissen', ORC utilizing exhaust heat from 2 Jenbacher (646 kWe) engines running on bio-gas from manure fermentation will be commissioned during May 2009.

4) There are a considerable number of quotations pending. The best chances are mentioned below:

a. 'Contract to be signed January 2009': similar unit as 'Eissen'
b. 'Contract to be signed February 2009': ORC utilizing exhaust heat from 1 Jenbacher (1400 kWe) engine running on bio-gas from manure fermentation
c. Contract to be signed February 2009': ORC utilizing exhaust heat from 1 Diesel (2100 kWe) engine running on bio-oil serving co-generation for a swimming pool.
d. Several applications on landfill sites, mine-gas, bio-gas
e. (see www.triogen.nl)