The Return of the Steam Engine

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ABSTRACT

This paper discusses current applications of steam engines in industrial systems and new technologies which are improving their performance. The primary advantages of steam engine use come from applications where current technologies are either not appropriate or cannot be scaled down in size. Examples are given showing cases where it is more cost effective (and efficient) to use steam engines including dispatched power, use of a lower grade gas turbine with a steam engine bottoming cycle especially in CHP applications with a large heat to power ratio, and in secondary heat recovery systems. For small systems, the steam turbine is not appropriate because of its small turndown ratio, sensitivity to steam quality, and high operating speeds. This results in available steam power being wasted. Steam engines scale down in size beautifully, work better with wet steam, and operate with very modest operating speeds.

Introduction

What do Indian sugar processors and small scale CHP systems in the U.S. have in common? They are ideal applications for modern reciprocating steam engines. While the technology is well established in the sugarcane business, it is only beginning to be considered as part of a CHP package. This paper discusses the modern use of steam engines and shows how adoption of this technology can allow increased energy efficiency in a variety of industrial processes.

The history of the industrial revolution includes a large chapter on the invention, introduction, and adoption of steam engines for all kinds of industrial applications and electric power. As time went on, the steam engine gave way to other prime movers and industry switched to electric motors and gas engine powered equipment. Power plants, still using steam, moved to steam turbines. Until recently, the existence of a reciprocating steam engine in an industrial plant was usually vestigial, with the device being kept around as an oddity or historical icon.

The rebirth of the steam engine is an interesting study in the development of technology. Often “the new” displaces “the old” in such a grand scale, that it is only later that the merits of the old technology can regain some visibility. Cogeneration is a good example of this, where new “ultra-high” efficiency power cycles were thought to make CHP almost undesireable. Clearly this has not turned out to be the case. Steam engines are getting a new look as energy prices get higher, even to the point of a technical prize being awarded for steam engine design.

This paper considers the classical advantages of steam power, and considers cases where it is presently not being harnessed because steam turbine technology is not appropriate from technical aspects or economics.

General Benefits of Steam Engines

The discussion of steam engines begins necessarily by considering the importance of steam itself. Not quite a magic material, steam has the benefit of a large latent heat of vaporization. This is used in many ways, primarily using the change in phase for energy storage and energy release. As steam changes phase, it gives up energy without changing temperature – a phenomenon which is very useful in chemical processing, the development of power cycles and in heat exchanger design.

Power systems utilizing steam also have the benefit of combustion external to the power prime mover. These so called "external combustion engines" differ from gas turbines or diesel combustion where the working fluid (providing power to a turbine or piston) is also directly involved in the combustion. The obvious advantage of external combustion engines is enormous fuel flexibility. All varieties of biomass, waste fuels, MSW, and industrial byproducts can be burned in incinerators or waste fuel boilers to make steam. This includes industries like forest products, where opportunity fuels and the need for steam create ideal conditions.[1]

Another form of waste which is often used to make steam is waste heat. As in the case of waste fuels, unusable heat from combustion or from cooling operations can be captured in boilers/heat exchangers designed for that purpose, in some cases utilizing more than 50% of the otherwise discarded energy.

Finally, it is important to note the role of steam in combined cycle power plants. Combustion systems and gas turbines discharge heat at very high temperatures. This high temperature heat exhaust results in poor to modest heat engine performance. If that heat is used to make steam which is then used in a power cycle, the resultant discharge of heat takes place at a much lower temperature, increasing the efficiency of the combined power cycle. This principle appears in the design of nearly all new combined cycle power plants which can achieved thermal efficiencies greater than 50% without cogeneration (even higher with it!).

Limitations of Steam Turbines

The question then turns to the prime mover. With high pressure, high temperature steam, one has really to choose between stream turbines or reciprocating or rotary engines. Their historical sequence is very well known with reciprocating steam engines being presented as indicating the beginning of the industrial revolution followed by the more efficient steam turbine some time later. Steam turbines are still ideal candidates for power, but there are tradeoffs from progressing up to turbine technology. The higher efficiency turbines have

[1] BIDINI, G. et al., "RECIPROCATING STEAM ENGINE POWER PLANTS FED BY WOODWASTE", Int. J. Energy Res., 22, 237—248 (1998)

- **Small turndown ratios** – turbines need to rotate at high speeds and are usually synchronized at 3600 rpm. With reduced pressure or flow rates, the fluid mechanics on the blading changes reducing system performance. This results first in degradation of performance as one moves from full load to part load followed by required shutdowns for operating conditions below acceptable levels.
- **Slow startup times** – blading and heat exchangers associated with turbines are very thin, but held together with large supporting bolts. To reduce thermal shock, startup times are long and the trend is toward even longer times on newer models.
- **Large capital costs and lingering economies of scale** – the complex nature of steam turbine systems, including significant water treatment, low pressure condensers, and high temperature and pressure tubing make initial costs high and reward larger installations where the ancillary costs are shared. With all the developments of gas microturbines and microhydro technologies, it is somewhat surprising that packages with competive costs are not yet available. Yet, the lower limit for use of steam turbines in CHP plants is a nominal boiler capacity of about 5 MW at present due to the lower electric efficiencies of small scale steam turbines and the higher price of the systems[2]
- **High cost for out-of-service time** – because of the large axis and horizontal orientation of most steam turbines, there is always the concern for warping of the shaft if the turbine is out of service for any reasonable length of time, resulting many cases in standby rotation of the shaft during its down period.

Beneficial Aspects of Steam Engines

Steam engines, in most cases, resolve these limitations and are the best chance for scale reduction in combined cycle power applications. In both DG and CHP applications, when steam is involved, turbines become questionable when the power output is below about 1 MW.

A list of permance advantages for steam engines would include:

- **Fuel flexibility** - allows for a portfolio fuel approach. This includes thermal solar with very attractive installation costs since the rest of the system already exists. One must recognize that with many biomass and other waste fuels, there may be more emissions concerns with sulphur, mercury and other non-standard pollutants.
- **Sensitivity to load** - System efficiency is insensitive to load and can respond to rapid changes in steam conditions
- **Low pressure combustion** – combined with no preheating allows for modest combustion temperatures and very little problem with NOx. Some new designs include coating the steam generator surfaces with an oxidation catalytic layer so that other emissions such as CO and unburned hydrocarbons can be reduced in a cost effective way
- **Modest speeds, pressures and temperatures -** are all in ranges which allow for safe and flexible operations Wear, noise, and maintenance are all improved because of low piston speeds.
- **Out-of-service and Startup** - startup is fast and steam engines can be out-of-service for long periods of time

[2] DECENTRALIZED BIOMASS COMBUSTION: STATE OF THE ART AND FUTURE DEVELOPMENT*, I. Obernberger, Biomass and Bioengineering, 14, no.1 pp. 33, 1998

- **Water Issues** - very modest water quality issues which results in reduced feedwater treatment costs. Also, the ability to handle wet steam in the pistons (even helping with lubrication) allows easy use of saturated steam

Modern Steam Engine Applications

Dispatched Operation

Most small scale power systems are envisoned as operating in a base loaded mode – running 24/7 and permanently removing the load from the grid. Where possible economically, this is a good application and serves to reduce the required capacity of the grid theoretically reducing the number of large power plants needed to support a power pool. It is increasingly obvious, however, that base loaded power plants lose money much of the time. Many power plants operate in a profitable mode only a few days a month[3]. This may be necessary for large fossil plants, but small scale operators facing daunting IRRs on their power projects need to consider operating in a dispatched mode – namely making power when it is economically smart to do so, and buying power when it is not.

Without directly acknowledging it, the power pool is already accepting dispatched power from renewables – wind and solar are dispatched by "God." There is no reason why clean or efficient power could not be handled in the same way. It is necessary to consider two broad types of dispatching. The first would be daily economic dispatching where a system might run only a few hours a day when "real time pricing" of electricity makes the spark spread favorable. In <1 MW situations, steam engines have many advantages. Design considerations in this case revolve around startup times and offload operations. Steam turbines have low torque at startup and are designed for full load operation. Steam engines have full torque at almost zero RPM making them ideal for systems with simple startup logic. Using new designs including steam buffers, the startup times and response to load changes can be as fast as a diesel engine.

The second would be seasonal dispatching, where either the industrial operation is seasonal in nature (agribusiness being the best example), or with combined cycle operations where steam power is used when space heating is not needed. This is where the opening comment about sugar factories is connected to other applications. The seasonal nature of those production facilities combined with the use of waste or opportunities fuels (bagasse) leads to common use of steam engines. While annocdotal, there are observations that "a reciprocating steam engine is more commonly used in Indian sugar industry than a steam turbine or diesel generating set."[4] Indeed, while the low capital cost of steam engine power is a critical design consideration, long out-of-service times and the ability to start up easily after a long layoff make the decision obvious.

Combined Cycle Applications

This application perhaps has the largest potential of those discussed in this paper. Because of economies of scale, small gas turbine or IC engine cogen systems often do not use

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[3] Includes personnal communication with Francis Sullivan, PSEG Fossil LLC

[4] Quote from Harsh Vardhan on website http://www.messiaen.co.uk/steam/mills/livesteam.htm

steam as a bottoming cycle during those times when waste heat cannot be used. In many cases waste heat is used for space heating in the winter only, leaving many months of the year when the system is operating only as a power source. This reduces the overall benefit of the CHP system. While it would be best to take power systems offline, such dispatching is often not economically viable. Hence systems operate while losing money and emitting more emissions than more efficient scenarios.

Consider a common, well designed, CHP application such as a industrial campus. Waste heat may be used in the winter for space heating, in the summer in support of absorption refrigeration systems, but over the shoulder months, there is little to no waste heat needs.

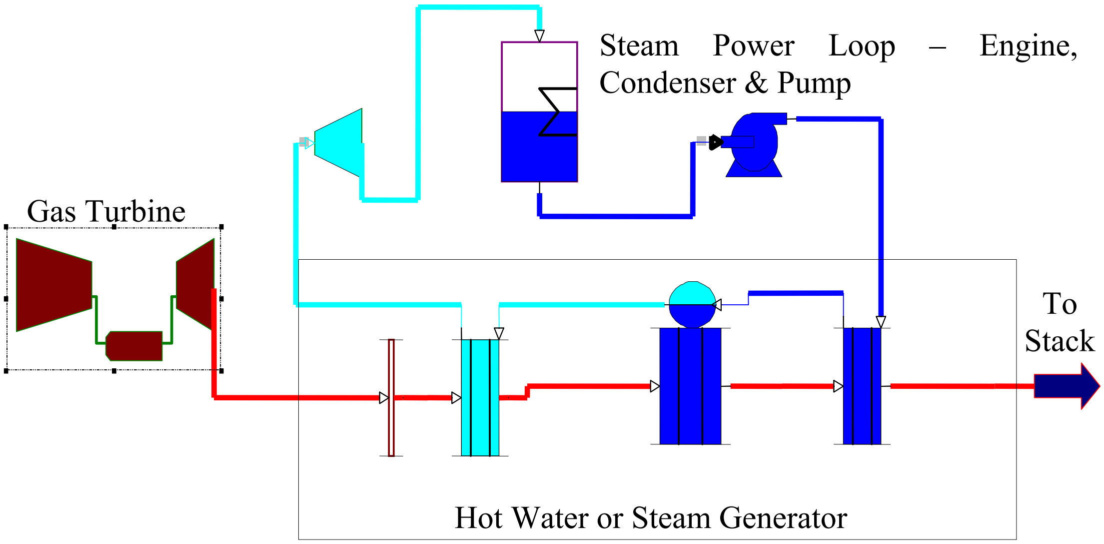
If the prime mover is 30% efficient and waste heat normally captures half of the waste heat, a typical CHP efficiency is calculated at 65%. But in reality, this is the maximum efficiency and for a significant fraction of the year the system only capitalizes on 30% of the energy consumed. While it is true that ideal applications have constant heat needs, allowing baseline operation and high efficiencies, the truth is that much of that potential has already been tapped. Continued market pentration of CHP requires novel system designs in applications with seasonal or periodic heating loads. In these cases, either nothing is installed, a system is put in place and operated only when profitable, or the system operates in base load mode losing money a significant amount of the time. A fourth possible outcome is to have a secondary use of the waste heat, in this case in a power cycle, as long as whatever the new prime mover is discharges heat at a lower temperature. The best candidate for this is a steam cycle which uses the waste heat from the "topping" cycle to make steam, uses a turbine or an engine to get power from that energy, and then discharges the remaining heat at a temperature usually somewhere slightly above ambient.

The thermodynamics that supports this model is very well established and is the basis for most combined cycle power plants. It is, however, rare to see such a combined cycle in CHP systems. The reasons for this have to do with both scale and economics – the steam turbines normally used in powerplants do not scale down in size for small power systems, and the costs usually do not make economic sense. This is especially true, because the bottoming cycle is only needed when waste heat cannot be otherwise utilized.

A simple case was studied using a power cycle modeling software (Gatecycle) with a small gas turbine (Solar Saturn 20) with and without a steam bottoming cycle. A diagram of the parts of the system is shown in Figure 1. In most cases because waste heat is already captured in an HRSG, the additional hardware needed is simply some steam prime mover, a heat exchanger/condenser and a pump to recirculate the water. Using normal temperatures and pressures in the gas turbine and a water pressure of 800 psi, the system shows a 70% increase in efficiency (39.64% from 23.21%) and output (1.94 MW vs. 1.14 MW). Using this as a guide, we can estimate the improvement of the overage efficiency of a CHP installation with the steam loop. Again, assuming that for 2/3 of the year 50% of the waste heat can be put to use, the maximum efficiency is 61.6% and the average efficiency is 48.8% for the entire year. Using a steam power loop this improves to 54%.

Clearly this is advantageous and the devil will typically be in the details. Use of steam engines will usually be required to reduce capital costs, and development of new compact heat exchangers makes it possibly to realize very compact steam generators creating a very high power density and power to material weight ratio which will also yield lower implementation costs.

Figure 1. Simple Combined Cycle Arrangement

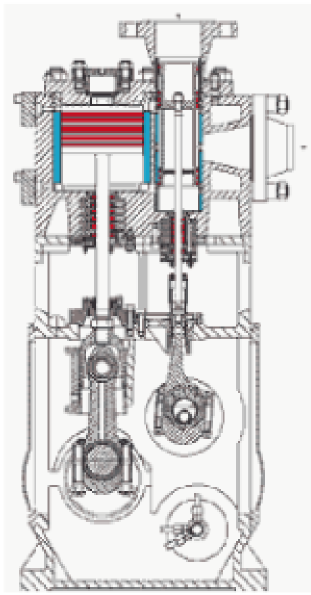


In combined cycle operations (or any steam engine application where efficiency is critical) the pressure on the exhaust of the steam engine must be less than atmospheric so that condensation of the steam will occur at temperatures near ambient.

As Secondary Energy Recovery

For many installations, primary waste heat is a challenge in itself, with hot combustion exhaust streams often being discharged to the atmosphere without any recovery at all. This waste heat source tends to be very hot and many applications can compete economically. However, there are secondary waste heat streams which can result in large energy waste and some companies are starting to recognize this. Steam engines are used at the Oberland glass factory at Bad Wurzach, Germany[5], for example, to recover secondary heat – similar to many applications where exhausts gasses are at low temperature. Primary exhaust from the glass furnaces is used preheat the combustion air, but cooling of the hot glass provides a secondary waste heat source which had been routinely discarded. This waste heat stream results in a flow of 5.5 tons/hr of superheated steam at 20 bars and 300 °C which is utilized by a 500 kW reciprocating steam engine made by Spillingwerk of Hamburg, Germany.

Figure 2. Spilling Reciprocating Steam Engine



[5] Data from EPC ENERGY GROUP LTD.

Cut Out the Middle Man – Steam Power Machines

With concerns about interconnection with power generation, some facilities are reluctant to make electricity, even when the price spikes to excessive levels. One simple way to get around this is to take certain motor driven equipment and have the ability to replace them with steam. As discussed in previous sections, this is unlikely to make economic sense except on a dispatched basis – using the steam driven equipment when electricity prices are high. Again, turbines would likely be unattractive for small systems, but steam engines are available to power compressors and pumps at small capital costs. In most cases there would have to be steam in a plant for this to make sense. Clearly this is an old use, but now companies such as Armstrong International Inc. are patenting new designs for so called "steam lizards", namely steam powered pumps[6].

One motivation for a renewed look at these systems is the need to be fault tolerant in grid interruption situations – steam powered equipment can continue to run or shutdown safely in blackouts. It is often not trivial to provide grid tolerant power because of the required match between electrical supply and load. If the power generation system produces more than can be used locally, the system must be able to backoff power, sometimes requiring duty cycles as low as 10 or 15%. If the opposite is true, that local generation is less than local needs, the facility must be able to shed load almost instantly, often requiring substantial rewiring of plants. Steam powered equipment, by its very nature, represents a perfect match between power generated and consumed totally eliminating this issue.

New Designs

One of the challenges to reintroducing technologies is to overcome the reasons the technology fell out of favor to begin with. Steam engines operate at 10-15% efficiency with normal designs. This is a small number when compared with steam turbines, but a large number when compared with discarding the energy as waste heat. However, several new approaches are promising a big increase in efficiency with a variety of schemes.

Figure 3. Enginion's "Steam Cell

Component Improvements

With changes in piston design, development of a compact steam generator and compressor, and the use of buffers for the steam and the condenser, the Swedish Ranotor system is promising efficiencies approaching 35%. The device includes two motors and two buffers intended to maximize time response to changes in load and efficiency. The focus is on keeping the steam engine oil free, as is the case with chillers and heat pumps where the working operates in

[6] Steam driven pump"; Patent Numbers: 06599096, 06602056; Inventor: Totten, Timothy K.;McNamara, Matthew R.; Assignee: Armstrong International, Inc.; Issue Date: 07/29/2003, 08/05/2003; Publishing Authority: US

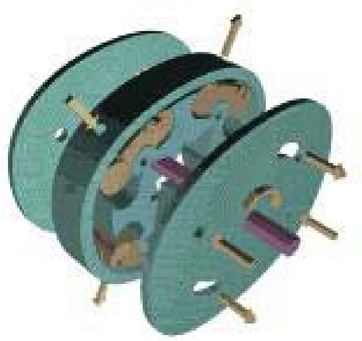
a closed loop and any contamination will reduce fluid life. The compact heat exchanger approach makes it possibly to realise very compact steam generators with excellent power density not common in steam boilers in large power plants. The high power to material weight ratio directly relates to lower capital costs.

Buffering provides a low cost thermal storage allowing a steam system to respond to load (or price) variations in electrical demand. The condenser buffer makes is possibly to condense large amounts of steam at a high rate without small vibration and noise – necessary in designs which will exist in inhabited spaces.

Rotary Designs

Many of the new designs for steam engines originate in the automotive industry but port very easily to stationary power applications. A good example of this is the German ZEE03 engine developed by IAV inc. which began as a classical piston engine – morphed to a multi-cylinder design and finally to a rotary design. It was intended, since its inception for applications in CHP and APUs as well as moving power systems. Now being commercialized by Enginion as the "Steam Cell", both the company and the product have been singled out for innovation[7]. The rotary design is very similar to screw compressors common in air systems. Either single or double scroll, they are very robust (like piston engines) and can be used with wet steam and even liquids. Rotation speeds scale to the flow rate of the steam and the electrical output is changed from DC to AC using normal inverter technology. The design is very compact making for ease in implementation, small capital costs, and low noise. Similar to modern screw compressors, they are also intended to operate oil-free, with a separate oil loop for cooling only. Screw-type engines can be operated with steam at low temperatures and pressures (200-400 °C, 25 bar).

Figure 4. The Quasiturbine Steam Engine



The Canadians are working along similar lines with their Quaziturbine steam engine (Figure 4). In their base design, an oval housing surrounds a four-sided articulated rotor which turns and moves within the housing, trapping the working fluid into four chambers.

As the rotor turns, its motion and the shape of the housing cause each side of the housing to get closer and farther from the rotor, compressing and expanding the chambers similarly to the "strokes" in a reciprocating engine. By selectively admitting and discharging steam, the four chambers of the rotor generate eight power "strokes" per rotor revolution which results in smooth operation at a large range of rotation.

[7] Enginion won the "Most Promising Company" award at the international 2002 Energy Venture Fair held in Chicago.

Conclusions

A review of the technology and possible applications of steam engines to industrial power and waste heat opportunities indicates that steam engines are likely to be part of the energy engineer's portfolio as we move forward. When economics and operational issues are factored into design decisions, it can often be the less sexy technology which needs a careful look. Steam engines, the technology that led us into the industrial revolution, still has an important role.

It would be useful to identify industry sectors or types of facilities that would be good applications for the new generation of steam engines, but it is likely that implementation will be eclectic. Clearly there needs to be a fuel source such as natural gas available and certainly facilities with processes that already utilize steam will be prime candidates. But it is likely that closed steam system designs will appear as ways to increase total efficiency of small scale power systems allowing them to qualify for rebates in clean energy programs throughout the country.