Expert opinion

Stirling machine in Alphagamma arrangement

for Fa. Frauscher Thermal Motors

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Stirling engines have been known for a long time; Robert Stirling's patent dates back to 1816, making the Stirling engine significantly older than the wide spread internal combustion engines. Nevertheless, the Stirling engine is hardly represented in any practical applications. At most Stirling machines are implemented in the field of cryogenic refrigeration and, more recently, as a micro-cogeneration unit. Instead, engine technology is dominated by internal combustion engines, and as a result, both a lead in R&D efforts and a cost advantage due to large-scale production have arisen here, which is difficult to overcome by other engine technologies.

However, with the abandonment of fossil fuels, niches markets are opening up where the Stirling engine is technologically superior compared to its competitors, so that the aforementioned drawbacks fade into the background. One area of this kind is the generation of electricity from lean gases as well as from solid biomass such as wood pellets or wood chips. These fuels can only be used by internal combustion engines after mixing with high caloric gases due to their low ignitability of after gasification as they are available in solid form, only. In the low power range and thus below the application of ORC technology, this forms a unique area for implementation of Stirling engines that in addition is becoming more significant day by day in view of the current debate on global warming and climate change. With the increasing number of pellet and wood chip boilers, Stirling engines offer the opportunity to generate not only heat, but also electricity without harmful CO_2-emissions.

Nevertheless, this idea is by no means new; there are already various companies that have tried to establish and market the Stirling engine in this application. After analyzing why none of them succeeded so far, two areas of technology can be identified which have so far prevented a successful market launch and a significant dispersion of Stirling engines running on lean gases and biomass: It is combustion technology on the one hand, and the mechanism synchronizing and connecting pistons to the electric generator on the other. This implies that the Stirling cycle itself and the implementation of this cycle in an engine is not the technical problem. Nowadays, Stirling engines offer competitive power-to-weight ratios as well as efficiencies comparable to other engines, if an air preheater is incorporated. However, it is well known that combustion technology in the field of biomass applications is not trivial. The aggravating factor in running a Stirling engine on biomass is that the heat must be extracted from the flue gases at high temperatures. It is therefore not without reason that companies such as Mawera, Hoval or ÖkoFEN are involved in the development of biomass-powered Stirling engines, whose expertise in biomass combustion technology is well established. For that reason, appropriate solutions are emerging, and some of them already have proofed their feasibility.

The mechanism, on the other hand, represents a problem in Stirling engine development that has so far been inadequately solved. This may sound strange at first, since mechanisms are developed and state of the art in many different variations. In case of a Stirling engine, however, the development of a proper mechanism is more difficult. Firstly, in stationary applications - in contrast to mobile units - extremely high demands are placed on lifetime with more than 50,000 operating hours and on

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maintenance intervals with more than 5,000 - 6,000 operating hours. Secondly, lubricating oil is avoided whenever possible and lifetime-lubricated bearings and dry-running guidings are used instead. Experience has shown that in case of oil-lubricated Stirling engines the penetration of oil vapour into the volumes of the Stirling cycle cannot be completely prevented, which in the long term destroys the engine, as both the regenerator is clogged by the oil and the steel alloys in the high temperature area become brittle due to carburization. As a consequence, all efforts in developing biomass-powered Stirling engines have failed so far due to glitches of the mechanism. The only unit of this type currently being launched on the market, the Pellematic Condens_e by ÖkoFEN, is a free-piston Stirling engine, hence, a Stirling engine that does not require a mechanism at all. In a free-piston Stirling engine, the pistons are connected to the casing by springs, thus forming an oscillating system, so that no mechanism is required for synchronization. The electrical power is generated via a linear generator connected to the working piston. Due to the forces to be controlled by the springs, however, the application of free piston technology is only suitable for small engines with power outputs from a couple of Watts up to a very few kW; the free piston Stirling engine installed in the Pellematic Condens_e provides an electrical output of 1 kW. In addition, linear generators show smaller efficiencies compared to rotating devices.

Larger Stirling engines rely for that reason on a dry-running mechanism offering a long life expectancy, and this is where the design of the Alphagamma arrangement comes in. However, the core of this design is not a new type of mechanism, which is attributed to the fact that in the past, there have been various proposals of this kind, all of which have failed either because of their complexity or the additional volume required and thus the cost. Instead, Frauscher Thermal Motors proposes a modified configuration of the Stirling cycle aiming at a reduction of the piston rod forces acting on the mechanism. This addresses the problem right at its root, and by this means leaves the option for any mechanism to be applied including the crank drive.

Up to now, three arrangements of Stirling engines have been distinguished, the so-called Alpha, Beta and Gamma configuration. Figure 1 shows the three arrangements schematically. It can be seen that the Alpha configuration is made up by two working pistons, while the Beta and Gamma configuration consist each of one working piston and one displacer. The displacer is characterized by the fact that it is exposed to the working gas pressure at its top and bottom side. Thus, a displacer only transfers small forces to the mechanism with respect to the pressure difference between working space and gear box, which are essentially determined by the cross-sectional area of the displacer rod. At this point, it should be added that the forces caused by the pressure difference between working space and gear box always account for the largest portion of total piston rod force compared to mass, friction and damping forces. Consequently, displacer pistons transfer smaller forces on the mechanism than working pistons, and for that reason Beta and Gamma arrangements are advantageous in this respect compared to the Alpha configuration.

The disadvantage of the Beta configuration, however, is that only special types of mechanisms, such as rhombic or four-joint mechanisms, can be applied, because of displacer rod and working piston rod are arranged concentrically. Hence, a crank drive is not suitable, which is why Frauscher Thermal Motors has limited itself to a detailed investigation of the Alpha and Gamma configuration with regard to the resulting piston rod forces.

The analysis revealed that a significant increase in cross-sectional area at the displacer rod in Gamma configuration causes an increase in the pressure force for the displacer. This fact on its own is not surprising, but in addition, this measure results in a reduction of the force at the working piston rod. This effect is significant, because the working piston transfers considerably higher forces to the mechanism than the displacer, since its entire cross section contributes to pressure forces. In the end, it is therefore possible to reduce the maximum forces exerted by the working piston on the mechanism by increasing the cross-sectional area of the displacer rod.

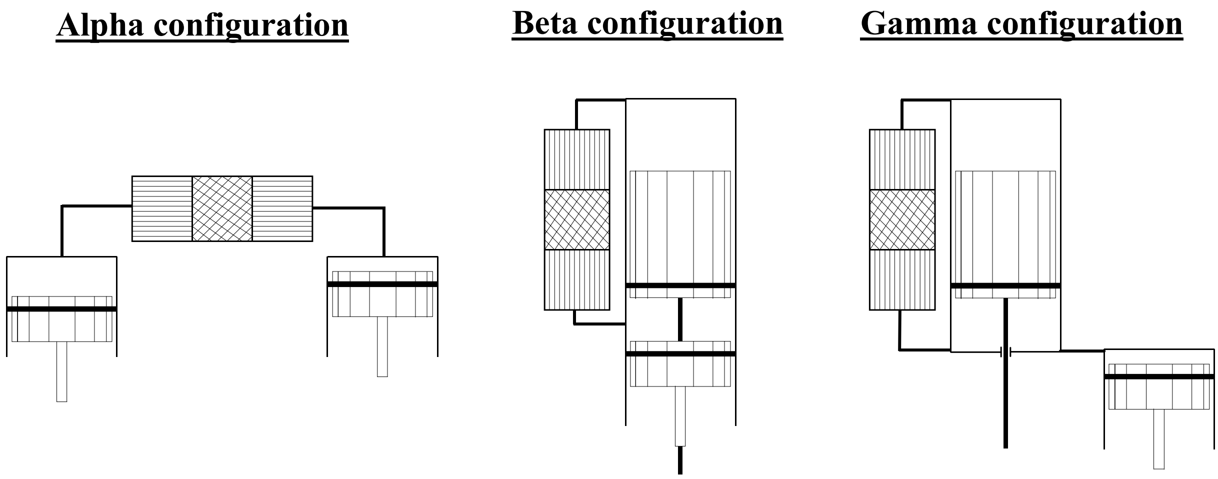

Figure 1: Stirling engine in Alpha, Beta und Gamma configuration

Figure 2 illustrates the correspondingly configured Stirling engine with a (vertical) displacer comprising of a considerably enlarged rod cross-sectional area and a (horizontal) working piston. The displacer thus resembles more a stepped working piston than a classical displacer, whose rod is simply meant for coupling the displacer to the gear mechanism. It should be noted that the design of a displacer as a stepped piston by enlarging its rod cross-sectional area is not new in itself, but has already been suggested elsewhere (e.g. Budliger 2000[2]). The objective was always similar with the redistribution of the mechanical work from the working piston to the displacer in order to achieve a more balanced system in this respect. However, the technical development of Frauscher Thermal Motors aims a little further by enabling the implementation in a compact design, which is patented.

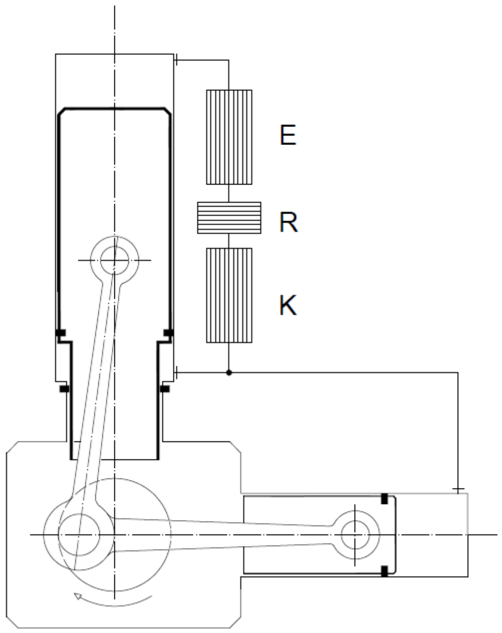

Figure 2: Stirling engine in Alphagamma arrangement

[2] Budliger, J.P.: „Simple Stirling engine as cogeneration unit in residential areas“, Proc. Europ. Stirling Forum 2000, Osnabrück, 22.-24.2.2000, p. 201-211

Since the arrangement of the Stirling engine is to be classified between the Gamma and Alpha configuration - it can be seen from Figure 2 that the Alpha configuration is achieved in case the rod cross-sectional area reaches the cross section of the displacer itself, it is titled Alphagamma arrangement (or Alphagamma configuration).

In order to provide a quantitative evaluation of the effect achieved, simple thermodynamic analysis, such as the isothermal model of the Stirling cycle, are suitable. Figure 3 shows the results of such calculations with respect to the maximum piston rod forces. It can be seen very clearly that the maximum piston rod force occurring is lowest in the Alphagamma configuration. With regard to the calculations, it should be noted that the Stirling engine in each configuration was trimmed to the same mechanical power output via the mean working gas pressure in order to maintain proper boundary conditions for the comparison. According to the isothermal model, the Alphagamma arrangement results in a reduction of the maximum piston rod force by 47.1% compared to the Alpha configuration and by 29.1% compared to the Gamma configuration, which can be considered a significant improvement. A review of these calculations by a more advanced differential model reveals similar results, as shown in Figure 3.

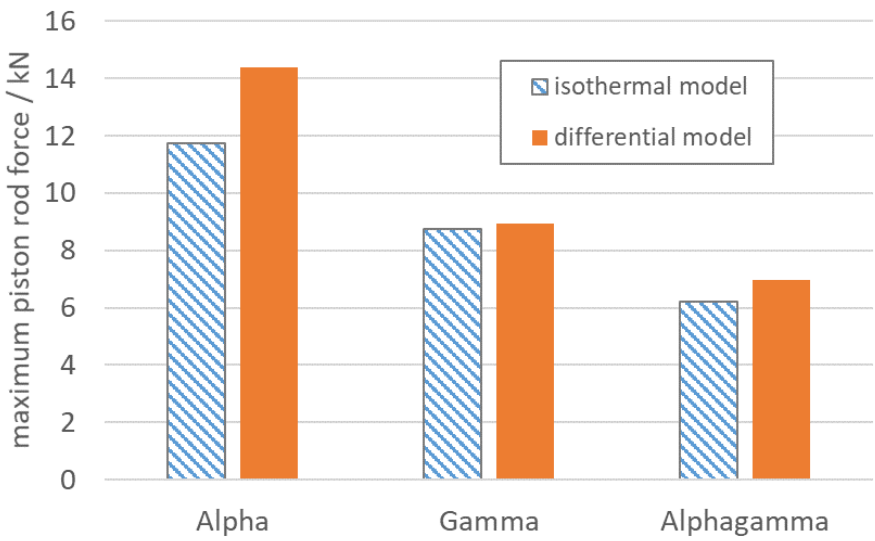

Figure 3: Maximum piston rod forces for a Stirling engine in Alpha, Gamma und Alphagamma configuration of the same mechanical power output

Thermodynamically, this result can be explained by the fact that the Alphagamma arrangement bears the highest potential for shifting the phase angle of the working gas pressure oscillation by the enlarged cross-sectional area of the displacer rod in a way that the piston rod forces on displacer and working piston are equalized. By this means, the maximum piston rod force is reduced while the total torque at the crankshaft remains constant. For this purpose, it is important to know that the oscillation of working gas pressure is not only caused by mechanical compression but also by thermal compression due to the different temperatures in the cylinder volumes. Without going into further detail at this point, it can be deduced from this observation that by optimizing the cross-sectional area of the displacer rod, an optimum with minimal forces on the piston rods can be found for every Stirling engine design in Alphagamma arrangement. In this respect, the result obtained is not limited to the design examined at Frauscher Thermal Motors. Instead, it is generally valid making the configuration all the more valuable, since it can be applied to any Stirling engine.

In this respect, the implementation of the Alphagamma arrangement by Frauscher Thermal Motors represents an important step towards the design of a proper mechanism for Stirling engines. This resolves the problem outlined above in the development and market launch of Stirling engines for the conversion of biomass into electricity and heat in the lower power range. In addition to this effect, which is highly desirable from a climate policy point of view, the Alphagamma arrangement may also succeed in establishing the Stirling engine in further applications.

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