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HIGH EFFICIENCY HEAT TRANSPORT AND POWER CONVERSION SYSTEM FOR CASCADE

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ABSTRACT

The Cascade ICF reactor features a flowing blanket of solid BeO and LiAlO_2 granules with very high temperature capability (up to ~ 2300 K). We present here the design of a high temperature granule transport and heat exchange system, and two options for high efficiency power conversion. The centrifugal-throw transport system uses the peripheral speed imparted to the granules by the rotating chamber to effect granule transport and requires no additional equipment. The heat exchanger design is a vacuum heat transfer concept utilizing gravity-induced flow of the granules over ceramic heat exchange surfaces. A reference Brayton power cycle is presented which achieves 55% net efficiency with 1300 K peak helium temperature. A modified Field steam cycle (a hybrid Rankine/Brayton cycle) is presented as an alternate which achieves 56% net efficiency.

INTRODUCTION

Before fusion reactors can move ahead to commercial development, technically sound approaches must be developed that are economically competitive, safe, and environmentally attractive. Innovative concepts are needed in many areas to facilitate commercial application. Cascade^{1,2} represents one such novel concept for the design of an Inertial Confinement Fusion (ICF) reactor. It utilizes a moving bed of solid lithium compound granules, held against the walls of a rotating chamber by centrifugal force, to capture and transport the fusion energy. The present design features a low activation reaction chamber concept using circulating solid lithium aluminate (LiAlO_2) as the tritium breeding and energy transport material. A surface layer of BeO granules protects the LiAlO_2 from the fusion micro-explosion. The concept is inherently simple, yet the high temperature capability of ceramic compounds allows both low cost and high efficiency. The reaction chamber/granule transport/heat exchange arrangement is shown in Fig. 1. The reaction chamber and blanket designs are presented in companion papers^{3,4}.

The primary coolant loop of the Cascade reactor possesses characteristics which also offer the potential for a high degree of inherent safety. First, the circulating bed of BeO and LiAlO_2 granules serves multiple functions as the heat generating, transport and exchange

medium. Second, it is not strictly a coolant loop since the circulating bed does not perform a cooling function, i.e., it does not remove appreciable quantities of heat from other components within the reaction chamber. Thus a loss of coolant accident has little meaning. Third, BeO and LiAlO_2 granules in the Cascade design do not produce any radioactivity with significant decay afterheat. Thus, a loss of coolant accident would have insignificant consequences were one to occur. Finally, since the blanket granules are solid, they present unique challenges in both heat exchange to a working fluid or gas, and in their transport around the primary loop. These challenges are addressed in this paper, in which we present the design of a high temperature granule transport and heat exchange system, and two high efficiency power conversion systems.

GRANULE TRANSPORT SYSTEM

The granule transport system provides the interface between the Cascade reaction chamber and the power conversion system. The centrifugal-throw transport system shown in Fig. 1 uses the angular momentum imparted to the granules by the rotating chamber to effect particle transport and thus would not require any additional equipment. It would, however, be limited to heights determined by limitations on the chamber rotational speed. The mechanics of material flow in the chamber are such that blanket material slides along the chamber wall under centrifugal action and issues from the chamber through an equatorial slot onto an exposed shelf on the outside of the chamber facing away from the chamber midplane. Transport of the high temperature (up to ~ 2300 K) granules begins with their removal from the shelf by a controllable scoop, which provides the primary reactor flow rate control. At the reference chamber rotational speed of 50 rpm, the centrifugal-throw system can adequately elevate granules to the top of the heat exchanger. As shown in Fig. 1, the granules then "cascade" through the heat exchanger giving up their heat and flow through hoppers back to the reaction chamber inlet locations.

Figure 2 shows a plot of the trajectories of particles forced off the shelf at various points along a removal arc. A chamber speed of 40 rpm and a 20% loss of rim speed were assumed in this figure. There are no convergent flows until the line of the first released particle's

Fig. 1. Cascade reaction chamber, granule transport and vacuum heat exchanger system.

Fig. 2. Trajectories of granules departing the chamber shelf via scoop action (non-optimized).

trajectory starts to re-enter the stream. The particle stream ejected from the loaded shelf by the control scoop is directed along a throw duct and caught in the heat exchanger. The heat exchanger tubes are completely submerged below the granular material. As material is removed from the chamber, an equivalent amount automatically flows through the heat exchanger and back into the reaction chamber.

HEAT EXCHANGER DESIGN

The heat exchangers used to recover the energy from the stream of solid LiAlO_2 and BeO granules flowing in a vacuum are a key feature of the Cascade power conversion system. The simplest approach is to use a simple shell and tube heat exchanger with the granules flowing by gravity in vacuum on the shell side and the secondary coolant inside the tubes. However, due to concerns of low heat transfer conductance in a vacuum, the use of helium gas in the interstices as a heat transfer and/or fluidization medium was also investigated. Four concepts were examined:

- Fluid-Bed Immersed-Tube Heat Exchanger
- Fluid-Bed Direct Contact Heat Exchanger
- Gravity-Flow Cascade Heat Exchanger with helium gas in the interstices
- Gravity-Flow Cascade Heat Exchanger in vacuum

The designs are described in detail in Ref. 2.

All four of the heat exchanger concepts evaluated are feasible and can result in practical designs. Fluid-bed concepts are self-distributing across their frontal area, whereas the gravity-flow concepts require mechanical distribution to minimize granule inventory. The direct contact heat exchanger, in which the working fluid is in direct contact with the hot granules, requires high helium pressure and has higher pumping power losses. Fluid-bed transfer areas are not significantly different

due to the good agitation and short particle contact time offered by the triangular pitch and flow baffles in the gravity-flow heat exchanger. Vacuum heat exchange surface area is approximately three times that of heat exchange area in a helium medium. However, the latter requires an active transfer lock system through which to pass granules in and out of the vacuum required in the reaction chamber. From a heat transfer perspective, all candidates are viable options for the Cascade heat exchanger.

From an overall evaluation, the selected design is a vacuum heat transfer concept utilizing gravity-induced flow-mixing of the granules over the heat exchanger surfaces. The conceptual Cascade heat exchanger arrangement is characterized in Fig. 3. Gravity-induced flow of particulate solids over the heat exchanger surfaces provides mixing similar to fluidization. Flow-splitter type distributors can provide relatively short residence times for the hot granules while maintaining uniform flow conditions over all surfaces. We selected a staggered-tube, horizontal array to enhance mixing. As shown in Fig. 3, once-through coolant tubes pass back-and-forth, ascending countercurrent to the granule flow. This heat exchanger arrangement has the advantage that it can operate in either gas or vacuum conditions. Major parameters of this gravity-flow Cascade vacuum heat exchanger are shown in Table 1.

Fig. 3. Gravity-Flow Cascade Vacuum Heat Exchanger.

TABLE 1
CASCADE HEAT EXCHANGER
DESIGN SUMMARY

Pressure	10 Pa
Number of Tubes	6200
Tube Diameter	2.5 cm
Total Heat Transfer Surface Area	84,000 m ²
Frontal Surface Area	500 m ²
Active Height	4.0 m

At the desired operating temperatures, the only functional materials are ceramics. The design incorporates SiC tubes in tension at modest stress levels. The major support structure is actively-cooled metal, incorporating a practical metal-to-ceramic joint. The design is modular, allows tube replacement and has passive tube-plugging capability.

POWER CONVERSION SYSTEMS

The high blanket temperatures possible with Cascade offer the potential for high thermal conversion efficiencies. In the initial phase of this work, we evaluated a number of power conversion system options with respect to net thermal efficiency versus the peak working fluid temperature. These include three primary power cycle options: Rankine, with water working fluid, Brayton, with helium working fluid (an ideal gas), and a Rankine/Brayton hybrid called the Field cycle,⁸ also with water working fluid; and secondary options, including combinations of these in the form of topping and bottoming cycles, differing working fluids, nonideal gas Brayton cycles, such as the supercritical CO₂, and dissociating gas cycles. In the second phase of this work, selected power conversion systems were tailored to accommodate the power fraction outputs and inlet/outlet temperatures of the Cascade blanket.

The results of the initial phase of this work are displayed in Fig. 4, which shows estimated net power conversion system efficiency versus peak working fluid temperature. This initial investigation showed that when the primary options are made reasonably sophisticated, such as by adding reheats, intercoolers, extractions, and the like, they become so efficient that the secondary options show no advantage. The latter were thus considered no further. In addition, with the temperatures achievable with a lithium aluminate blanket with a surface layer of BeO, net thermal conversion efficiencies in the range of 50% to over 60% were possible with the three primary cycles.

Fig. 4. Net efficiencies vs. peak working fluid temperature for several power cycles.

Figure 4 shows that steam cycle efficiency increases rather slowly with increasing superheat temperature. This is because such increases increase average heat addition temperature very slowly. The slow variation with temperature can be exploited in fusion reactors where blanket chemistry limits coolant temperatures to low values. As shown in the figure, adding reheats does help. With three reheats, steam cycle efficiencies of over 40% can be achieved⁶ at peak temperatures of only 648 K (707°F). Because of the high efficiency at moderate temperatures, the Rankine cycle is a useful fallback. However, Cascade blanket temperature are potentially higher and thus the steam cycle will be considered no further. The Brayton and GA-modified Field cycles are discussed below.

Brayton Cycle

For highest efficiency, the Brayton cycle with ideal gas compression requires the highest difference between average heat addition and average heat rejection temperatures. This difference can be increased, without increasing maximum or minimum temperatures, by dividing the compression and expansion into stages and adding intercoolers and reheats. As the number of expansion/compression processes increases, the cycle approaches an isothermal cycle, i.e., the Ericsson cycle. This is the most efficient limit for the Brayton cycle and the term Ericsson is often used for any Brayton cycle having more than one reheat and intercooler.

As seen in Fig. 4, the Brayton cycle is capable of very high efficiency provided one can achieve turbine nozzle inlet temperatures over 1200 to 1300 K. This is easier to achieve in an open-cycle gas turbine burning fossil fuel than in a closed cycle because heat addition does not have to pass through material walls. But even in that case, consideration must be given to the highly stressed turbine blades. In both open and closed systems, ceramic blades must be considered for temperatures higher than 1200 K, although some Hastelloys retain strength to 1300 K.

Fig. 5. Pressure-temperature diagram of Brayton cycle.

Figure 5 shows the pressure-temperature plot for the Brayton cycle optimized to the Cascade blanket heat delivery line, assuming a minimum 300 K log-mean temperature difference across heat exchangers. Although temperature-entropy diagrams would present the same information, P-T plots are more suitable for an ideal gas, and are simpler. Heating is represented by near-horizontal lines while compression (or expansion) are shown by lines steeply sloping up (or down) and to the right (or left). The path around the cycle is clockwise. The net power conversion efficiency is 54.8%. This is 73% of the Carnot efficiency calculated using the average heater temperature, $< T_{in} >$, of 1140 K. The optimum overall pressure ratio is 2.3.

Brayton cycle efficiency is a function of pressure ratio as well as temperature. The pressure ratios around the cycle must be optimized for optimum net efficiency. The adiabatic efficiencies of the turbine and compressor are also a function of pressure ratio. (This is also true of the Field cycle discussed below.) The assumed variation of compressor and turbine adiabatic efficiency with pressure ratio assumed in this analysis was taken from Ref. 7. The assumed heat exchanger pressure drops were generally 1 to 2%, depending on temperature rise. It is noted that, in general, pressure drop requirements set the lower limit on absolute pressure.

A block diagram showing flow paths and temperatures for the selected Brayton cycle is shown in Figure 6. While ceramics may be required for heater 3 and the inlet turbine nozzle, not only can the turbine blades be metal (much of the helium expansion is in the nozzle), but the lower temperatures reduce the demands on those components that must be ceramic. Furthermore, the large log-mean temperature difference of 949 K for heater 3 substantially reduces the size and cost of this heat exchanger. The flexibility also exists to lower the heater 3 granule temperatures.

Field Cycle History

In 1950, J.F. Field proposed a power cycle that was a blend of the Rankine and Brayton.⁵ Its appeal was

Fig. 6. Block diagram of reference Brayton cycle.

based on the fact that (see Fig. 4) efficiency gains with temperature are greater for Brayton than Rankine cycles but, to achieve good absolute efficiencies in pure Brayton cycles required high temperatures. His hybrid cycle was intended to bridge the gap.

The essential elements of the original cycle proposed by Field are as follows. Wet steam is compressed to saturated vapor, heated by regeneration, heated further by heat addition and expanded through a high pressure turbine. After passing through the other side of the regenerator, the stream is split in two. Part is expanded through a low pressure turbine, then condensed to liquid and recompressed. The other part, still superheated, is mixed with the compressed liquid to bring it back to the moist steam at the compressor inlet.

By compressing moist steam and liquid, the work of recompressing the working fluid was substantially reduced and so the temperature spread between heat addition and rejection could be lowered. However, with wet compression in an axial compressor, the droplets would be centrifuged out. Radial blade or centrifugal compressors experienced other design or efficiency problems of their own. In addition, even if the droplets remained in the flow stream, the droplet evaporation time could be longer than the residence time in the compressor, thereby raising the work of compression because compression would essentially take place with dry steam.

Furthermore, the Field cycle did not show enough advantage over the Rankine cycle at temperatures com-

patible with then-contemporary materials, and thus did not gain in popularity. A subsequent paper⁶ explored some useful variations of the cycle, some of which have been adopted here. Below, we propose additional modifications which overcome previous concerns, and explore the temperature regime of 1000 to 1400 K, where the cycle seems most attractive.

GA-Modified Field Cycle

Figure 7 shows a temperature-entropy plot of the Field cycle as modified for present-day application. Parameters displayed in the figure are for the reference design discussed below. The T-s plane is used here rather than the P-T because it fully describes a nonideal fluid like steam. The controversial wet compression has been replaced by three stages of dry compression with liquid injection between stages to bring the steam back to saturation. Conventional axial compressors, well-developed by the aircraft industry, can now be employed. The feedwater is compressed to about 6 atm above the final compressor inlet pressure to ensure atomization in the mixing chambers. Even though the steam is dry, compression near saturation is still preferable. The compression work over 100-200 psia is half that needed in the ideal gas region for steam (above 800 K). Clearly, compressing the liquid portion is easiest of all.

Also shown in Fig. 7 is a reheat and one feedwater extraction. The reheat temperatures and high pressure turbine (HPT) expansion ratios have been tailored to match the heat line of our reactor. In this case, two regenerators are used. The reheat also decreases low-pressure turbine (LPT) exit moisture to tolerable levels (below 13%). Efficiency is fairly insensitive to extraction pressure. The latter is thus chosen so as to minimize ducting size and in-leakage. A simple open extraction heater is all that is required.

Fig. 7. The GA-modified Field cycle with dry compression, one reheat and one feedwater heater.

Fig. 8. Block diagram of reference Field cycle.

The plot of efficiency versus peak steam temperature in Fig. 4 for the GA/Field cycle assumes equal main steam and reheat temperatures and equal pressure ratios for the two high pressure turbines. As with the Brayton cycle, these pressure ratios are optimized for maximum efficiency. Only one regenerator is required in this case. It is seen that, at 1800 K, the practical limit for metal heaters, over 58% efficiency is possible. Over 80% is possible at 1000 K, for which 300-series stainless steel is adequate at moderate steam pressures.

An advantage of this cycle is the flexibility in operating pressures even though it operates near the two phase region. As with Brayton cycles, pressures must be high enough to keep heat exchanger pressure drops low. Here we assume 58 atm (850 psia) peak will suffice. Note that the hot side of the regenerator is not at the minimum pressure (0.048 atm), which would produce unacceptable pressure drops, but at a fairly high intermediate value of 13.6 atm. A simple liquid compression Brayton cycle with steam does not operate this way because the regenerator pressure drop on the low-pressure side would be prohibitive.

Another advantage to the cycle is that overall pressure ratio is reduced from 8000 or so in a Rankine cycle to about 1200. HPT blade heights are therefore high enough for good efficiency even at low power levels. And because less steam flows through the LPT compared to a conventional Rankine cycle, last stage blade heights are about 2/3 as high.

Figure 8 shows a block diagram of the reference GA/Field cycle of Fig. 7 as applied to the Cascade reactor blanket. Steam temperatures are chosen to match the reactor zone heat inputs, while maintaining 300 K minimum log-mean temperature differences. Because the steam pressure in the high temperature heater is only 28 atm, it can probably be made of a Hastelloy metal, an appealing result particularly considering the achieved efficiency of 56%. The mixers shown in the figure are merely tanks for mixing the liquid and gas streams. The flow splitter is simply a regulated T-intersection. Note the modest pressure ratios shown in Fig. 7 for the EPT and compressor stages, which are conducive to good adiabatic efficiency and ease of design.

CONCLUSIONS

The design of a high temperature granule transport system which requires no additional equipment other than that required for clearing the reaction chamber appears practical. At the design chamber speed, the centrifugal throw system can adequately elevate granules to the top of the heat exchanger. A vacuum heat transfer heat exchanger concept was selected which uses only gravity-flow of the granules over the heat exchange tubes. Heat transfer areas are reasonable and the mechanical arrangement appears feasible.

Two power cycles were explored for application to Cascade: the regenerative Brayton cycle using helium, and the Field cycle using steam. We found that with the Cascade heat line, a simple once-through Brayton

cycle with no reheats gave an efficiency of 54.8%. Furthermore, this efficiency is achieved this with 1300 K peak helium temperature, possibly in the range of some Hastelloys. The low helium temperature also eases heat exchanger design due to the large driving temperature differentials possible with ceramic primary side granule.

With the Field cycle, we adopted a modified version with dry compression, one reheat, and one extraction. It appears to have attractions that are worth further inquiry. Net efficiencies of 56% are achieved, also with peak steam temperatures of 1300 K. The Ericsson and Field cycles match closely in terms of performance, equipment requirements and developmental needs. On the basis of perceived advantages in tritium recovery, the Ericsson cycle is chosen as the reference design for Cascade. Other power cycles, such as dissociating gas Brayton, Supercritical CO₂ Brayton, and topping and bottoming cycles show no advantage over sophisticated Brayton and Field cycles. The Rankine cycle still is best below 850 K, and is considered as an everpresent fallback.

The Cascade concept thus offers the potential for developing into a reactor which fulfills the high inherent safety potential of fusion in a reactor embodiment which is environmentally and economically attractive.

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