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GAS COMPRESSION BY JET PUMP COOLING

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Abstract

In the present state of art of the thermal engines using gaseous medium, the exhaustion temperature is often far beyond the ambient. The intake and the outlet of the working substance — mostly air, steam or other hot gases — require power resulting in reduction in net throughput of the engine. The power requirement can — in many cases — be reduced, eliminated or even extra power can be gained by application of the compression tube. The compression tube is a device, which increases the pressure of the flowing gaseous medium. The pressure increase comprises two well-known effects: the ejector effect and the effect of the cooling on the stagnation pressure of the flowing gas. The compression tube can be recommended for stationary thermal engines, such as Diesel engines, stationary gas turbines of flue gas removal systems of boilers or ovens. Since the compression tube cools the gas, thus if it is applied in the exhaustion system of the engine, other methods for use of the enthalpy of the exhaustion gas — e. g. recuperators, waste heat recovery boilers, etc. — are excluded as waste heat utilization, at least in the temperature range of the compression tube.

Keywords: gas turbine, cycle efficiency improvement, gas compression by hot water ejector.

Introduction

The present paper refers to a method of compression tube for increasing pressure of gaseous medium by means of injecting high velocity cooling substance into the hot gas flow [1]. The appropriate injection of the cooling substance in the hot gas results in both cooling and ejector effect, and each of them increases the stagnation pressure of the gas flow. The compression tube is generally applicable if relatively high gas temperature is available, and the pressure increase of the gas provided by the cooling is valuable.

The temperature drop necessary to produce the pressure increase required can be — within limits — regulated by changing the ratio between the ejector and cooling effect. If the temperature drop, i. e. the cooling effect is negligible then the ejector effect dominates and produces the desired pressure increase. The ratio of these two effects is the subject of careful consideration when designing the compression tube.

The stagnation pressure gain of a gas flow means that a continuous gas stream can be developed and maintained from a lower pressure space to a higher pressure one. If the higher pressure is the ambient, then the lower pressure is under the atmospheric pressure, i. e. the gas would flow from 'vacuum' to the normal atmosphere. In gas turbines or internal combustion engines either the admission pressure can be elevated above the otherwise attainable pressure or the exhaustion pressure of the engine or turbine can be set under the ambient pressure by the application of the compression tube. Of course the pressure 'manipulations' could also be applied simultaneously. By that means the engine or the turbine will be able to put out significantly greater power with unchanged or only slightly modified mass flow rate and by the same fuel consumption. Generally speaking, the method and device suggested is able to maintain continuous gas flow from a lower pressure space to a higher pressure one without external mechanical power input (such as fan, compressor, etc.). It indicates the further possible application area of the compression tube, which are the flue gas channels at boilers or furnaces and other hot gas ducts where pressure gain is advantageous.

The Compression Tube

The very complex thermodynamic and aerodynamic processes in the compression tube can be calculated by applying the momentum equation, the energy equation, and the Gibbs-Dalton law, if the gas mixture is assumed to obey the perfect gas law. The analyses [2] are most conveniently carried out by considering three components of the gas flow: the gas to be compressed, the liquid part of the cooling medium (here below: water) and its evaporated mass flow (i. e. vapor). The components have different physical properties and other characteristics (e. g. velocities), but in the optimum case at the end of the mixing and cooling process a homogeneous multicomponent gas flow leaves the cooling-mixing section of the compression tube.

The analyses indicate — which is otherwise a well-known fact — that the greater the gas velocity the more effective is the cooling to increase the gas stagnation pressure, thus high gas velocity is needed in the cooling mixing section of the compression tube for the effective compression. The velocity of the gas mixture flow in the cooling-mixing section of the compression tube can be either subsonic or supersonic depending on the pressure gain requirement, i. e. the pressure difference between the intake and outlet of the tube. The greater pressure gain needs supersonic flow in the cooling-mixing section, thus the compression tube is called 'supersonic'.

The cooling medium injection is always supersonic to provide appropriate jet-pump effect. If the gas mixture flow is also supersonic, then static shock wave needs to be developed to decelerate the gas flow to subsonic speed after the cooling-mixing section of the compression tube.

The requirement of the high velocity implies that both the subsonic and supersonic compression tube comprise a section to accelerate the flow of the gas to the appropriate high, either subsonic or supersonic speed. The section where the gas flow to be compressed meets the injected high velocity cooling-mixing medium and where the changes of enthalpy and momentum take place, — increasing by this way the stagnation pressure of the gas flow — is the cooling-mixing section of the compression tube. After the processes of acceleration and the cooling-mixing, a special section is needed, in which the high speed gaseous flow, — the gas and vapor mixture — is decelerated to the outlet velocity. The outlet speed should be low to reduce as much as possible the exhaust losses. This last section of tube contains, in case of supersonic compression tube, the static shock wave to decelerate the flow from supersonic to subsonic range.

The accelerator section of the compression tube is either a normal confusor in the subsonic case, or it is a Laval nozzle in the supersonic compression tube. The acceleration in the Laval nozzle can be considered as an adiabatic process, mainly due to the very short residence time. In the nozzle the enthalpy of the gas inflow is transformed to kinetic energy, and in the narrowest cross sectional area the local speed is equal with the local sound velocity, and in the outlet of the nozzle the flow is supersonic. The subsonic acceleration (and also the deceleration: Ventury tube) can be realized by simple area changes, the continuity of the flow will determine the actual velocity and static pressure values, thus in this case the only influence factor is the area change.

For the acceleration of the gas flow to the supersonic velocity range a 'critical' pressure difference must be maintained between the inlet and outlet cross section of the accelerator to reach the actual sound velocity (Mach $= 1$) in the throat of the Laval nozzle and for the further acceleration (Mach > 1) after the throat additional pressure drop is needed. To build up the desired pressure ratio between the inlet and outlet of the Laval nozzle, basically two ways can be chosen: either the inlet pressure can be elevated or the outlet pressure should be decreased. In most cases of the compression tube application, the first option cannot easily be applied, mainly because the Laval nozzle inlet pressure is equal with the characteristic pressure of the adjacent engine or machine (e. g. internal combustion engine or gas turbine exhaust pressure), and these characteristics many times cannot be, sometimes must not be modified.

It means, that for the build-up of the supersonic flow in the Laval nozzle of a supersonic compression tube, a special 'start-up device' is needed to create the necessary pressure difference between the intake and outlet of the Laval nozzle. The requirement of pressure difference can be fulfilled by creating a 'low pressure pit' after the Laval nozzle, in which the flow is supersonic and which is built up by the start-up device. It is in contrast to the subsonic compression tube, where simple area change is sufficient to accelerate the gas flow without any special start-up equipment.

If the inlet pressure of compression tube cannot be increased to develop supersonic flow through the Laval nozzle, then the best, most simple method to create the vacuum which is necessary to develop the supersonic flow, is to apply saturated hot water ejector (also called 'jet pump') as start-up device. The start-up equipment for the compression tube is similar to, or rather identical with those saturated hot water ejectors, which are applied in supersonic wind tunnels to maintain the supersonic flow for the aerodynamic experiments.

The start-up jet pump installed at the tail end of the compression tube should be able to provide the necessary vacuum in the compression tube, i.e. the pressure ratio needed to accelerate the flow through the Laval nozzle to the required supersonic speed. As the pressure is decreased and the supersonic speed is developed generated by the 'sucking effect' of the start-up device, the cooling in the cooling-mixing section is immediately put into operation and begins to work, i. e. the gas flow is immediately cooled at the moment the flow is supersonic. After the cooling is switched on, the start-up jet pump can be shot down thus the start-up device is in operation only for a few seconds.

As the start-up device is shut down, the ambient pressure 'penetrates' into the compression tube from the tail end of the tube, which is opened to the atmosphere, i. e. a normal shock wave begins to move up-stream into the compression tube. Provided the geometry of the tube and the inlet and outlet pressure ratio are appropriately designed, the shock wave will stop at the end of the supersonic cooling-mixing section in the compression tube. The up-stream movement of the shock wave will be stopped in the cross-section of the tube where the subsonic and the supersonic decelerator meet each other.

Since the subsonic decelerator is a diffuser geometrically and the supersonic decelerator is a confusor geometrically, the shock wave will stay in the neck of the compression tube, which divides the two parts from each other. The shock wave is a velocity 'converter', i. e. it converts supersonic flow into subsonic one (and it is the only way available to slow down supersonic speed) and the shock wave increases the temperature, density and static pressure of the flow. By the start up device the supersonic 'pressure pit' and the necessary pressure ratio in the accelerator Laval nozzle at the front end of the tube can rapidly be developed and by the cooling-mixing processes further maintained.

The gas to be compressed leaving the accelerator section and having the appropriate either subsonic or supersonic velocity enters into the cooling-mixing section where it meets the high speed cooling substance.

The processes taking place in the cooling section of the compression tube are extremely complex because the evaporation of the cooling water results in changes of the volume flow rate in the tube, complex momentum and energy exchanges take place between the high speed, continuously evaporating water droplets (and their vapor shells) and the slower hot gas main stream to be cooled. These phenomena can be followed by theoretical calculations [3], nevertheless for the appropriate design of the cooling section of the compression tube profound experimental investigations are essential. Basically two main governing processes occur in the cooling section: exchange of enthalpy and exchange of the momentum between the gas to be cooled and the cooling medium. As the cooling water molecules are evaporating they become to be part of the gas stream and they decrease the enthalpy and increase the momentum of the main gas stream. For the theoretical analysis the gas mixture can be assumed to obey the Gibbs Dalton law. By the momentum exchange the continuously developing vapor cloud is decelerated, while the main gas flow is accelerated [4].

The cooling-mixing section of the compression tube need to meet several criteria to be effective. The most important conditions are:

- The processes of cooling-mixing have to be rapid ones, taking place in a short period of time. Because the cooling of the gas stream and the high velocity of the flow jointly provide the effect of the increase of stagnation pressure, it is desirable to develop immediate, very rapid prompt cooling to avoid long run of the gas stream at high speed. The relatively long residence time or long path of run in the high velocity cooling section of the compression tube can cause substantial friction losses.
- It can be proved on the basis of the Reynolds analogy of the thermodynamic and aerodynamic 'picture' of the gas flow, that the cooling resulting in stagnation pressure increase can only be volumetric effect, because on the surface of the flow the required heat flux for the cooling cannot be developed [2]. It means that the cooling material has to be 'injected' into the gas stream, whatever would be the cooling effect (physical or chemical processes or both). Thus, the cooling medium (or media) must not be environmentally harmful, because even in the

case of the recovery of the cooling media, some exhaustion to the ambient by the main gas stream seems to be unavoidable.

- Theoretically, the inappropriate, low inlet velocity of the cooling medium can cause severe pressure drop, because of the drag force needed to accelerate the mass of the cooling material from the initial inlet speed up to the main gas stream velocity. The higher inlet speed of the cooling medium, the lower of the drag force loss, and if the two velocities are equal then the drag force loss is zero. On the other hand, if the inlet speed of the cooling substance is greater than that of the main gas stream, then thrust is produced, which results in stagnation pressure gain. Because of the irreversibility caused by the mixing of the two media having different velocities — namely the gas to be cooled and the cooling substance — the total stagnation pressure, calculated for all components of the gas stream, decreases if any velocity difference exists, although if thrust is provided by the high velocity cooling medium, the stagnation pressure of the original gas flow would increase.

Taking into consideration all of these requirements, the most effective cooling can be provided by using water evaporating in the hot gas stream [5]. In special cases, endothermic chemical reactions can also be considered, but the operational temperature range of the compression tube and the time requirement of the cooling represent severe constrainment for the applications of chemical reactions. Cooling by water injections has several advantages:

- The cooling process, i.e. the water evaporation could be very rapid if the cooling water enters into the hot main gas stream in form of small droplets, and if the droplets are in saturated state, i. e. in 'wet-bulb' conditions [6]. In the saturated state the evaporation is more volumetric than surface phenomenon, thus the whole mass of a given droplet changes phases simultaneously, resulting in a very fast cooling effect [7].
- Because of the great latent heat of the water vapor (it has one of the greatest among the available media), the specific cooling capacity of the water is large, thus the cooling mass flow required is relatively small. The time requirement and the specific cooling effect of the evaporation of water is very favorable, even if it is compared with other possible endothermic chemical reactions.
- Last but not least the water is generally available, environmentally not harmful, relatively cheap, 'easy to treat' substance.

To obtain appropriate cooling effect very fine, saturated droplet 'cloud' is required entering into the hot gas stream with high speed to provide thrust to increase the stagnation pressure of the main gas stream. The device which is able to meet these requirements is a very simple one: the saturated hot water ejector similar to that built in the start-up device.

The saturated hot water jet pump is basically a Laval nozzle [8] connected to a water tank in which the water is in saturated state at the appropriate pressure. The pressure in the tank is needed to provide the necessary pressure difference in the Laval nozzle. The water, while getting through the nozzle, expands and partly evaporates [9].

The measure of the evaporation depends on many factors, such as the required outlet speed of the injector, the inlet and outlet pressure of the nozzle and their difference, the geometry of the nozzle, etc. It can be assumed that appr. 10 – 15% of the cooling water mass flow will change phase, i. e. evaporates [10]. This quantity is lost from the point of view of cooling, but the drastic specific volume increase due to the evaporation provides very great acceleration in the nozzle, thus the exit velocity of the cooling water will be very high [11]. The almost two hundred times greater specific volume of the evaporated portion of the cooling water also assures very fine droplet formation [12] in the nozzle (the volume flow rate ratio between the water and the stream is appr. 1 to 20, while the mass flow rate ratio is appr. 88 to 12). Obviously, there is certain slip between the stream and the water droplets in the nozzle, but due to the volumetric character of the vapor formation in the nozzle, this velocity difference between the vapor and water cannot be significant.

The application of the saturated hot water jet pump to feed the cooling medium into the gas stream makes possible to develop very high velocity, evenly distributed water spray formation consisting of very fine droplets. The high speed water-vapor mixture leaving the jet pump has strong ejector effect, which finally results in stagnation pressure gain in the compression tube [13]. The ejector effect depends on the ratio of the mass flow of the cooling medium and that of the gas to be compressed, the velocity difference of the two substances, the geometry of the compression tube, etc.

The cooling medium, i.e. the saturated water meets the hot gas stream where this latter's velocity is great at the outlet of the accelerator section, which is the inlet of the cooling-mixing section of the compression tube. The velocity of the gas and the gas vapor mixture while cooling in the appropriately designed compression tube, remains high to assure maximum stagnation pressure gain. In case of the optimal design of the compression tube the cooling water totally evaporates up to the end of the cooling-mixing section of the compression tube and just after the evaporation deceleration begins [14].

At supersonic cooling, the cooling-mixing section of the compression tube is closed by the static normal shock wave, transforming the supersonic flow into a subsonic one. If the main gas stream is subsonic, the subsonic decelerator is a normal diffuser, which is adjusted to the cooling-mixing section. The subsonic flow, leaving the static normal shock wave is also to be further decelerated by a subsonic diffuser. Both the subsonic and the supersonic cooling-mixing take place in the high velocity, low pressure section of the compression tube. As it has been mentioned, it is the pressure pit, which need to be developed by the start-up saturated hot water jet pump at the beginning of operation in the supersonic case. In the subsonic cooling, there is no need for such a start-up device. The cooling-mixing section of the compression tube is situated between the accelerator and the decelerator section.

The history of the evaporation of the saturated water droplets is very complex [15], the initial size of the droplets, the velocity differences between the droplets and the gas flow, the physical properties of the droplets and many other factors influence the processes of the cooling-mixing section of the compression tube. Through the droplet life time in the cooling-mixing section, intensive energy and momentum exchanges occur. The energy exchange is associated with the enthalpy decrease of the gas to be cooled and the enthalpy increase of the droplet molecules for evaporation. Further the energy exchange associated with changes in kinetic energy between the evaporated liquid and the gas surrounding providing thrust force for the gas and drag force for the vapor and for the droplet in the vapor, i.e. the velocities approach to each other [16].

To provide efficient jet pump effect the momentum exchange associated with the deceleration of the evaporated and unevaporeted liquid is essential. The thrust is provided partly by the high speed steam developed in the saturated hot water jet pump, partly by the liquid droplets leaving the saturated hot water jet pump [17]. The droplets will evaporate later in the cooling-mixing section of the compression tube providing also high speed vapor.

The total stagnation pressure at the inlet of the cooling-mixing section of the compression tube, i. e. the sum of the stagnation pressure of the cooling substance and that of the main gas flow to be compressed, exceeds the value of the total stagnation pressure at the outlet of the cooling-mixing section, i. e. that of the vapor gas mixture. Because of the irreversibility of the mixing process, nevertheless the stagnation pressure of the mixture leaving the cooling-mixing section is substantially greater than that of the main gas stream entering into the cooling-mixing section. The deficit in the stagnation pressure is provided by the saturated hot water jet pump. The cooling medium at the ejector outlet has great stagnation pressure, but the power requirement to produce this high value of the stagnation pressure is not significant because it means compression of water or other substance in liquid phase.

The ideally constant high velocity, more exactly, the constant Mach number in the cooling-mixing section of the compression tube can be maintained by the appropriate shape of the compression tube, i. e. by cross-sectional area change of the flow. It is the most important independent parameter to be designed. If the cooling is supersonic, then at the end of the cooling-mixing section of the compression tube a static normal shock wave takes place, which represents entropy increase and loss in the stagnation pressure. The supersonic flow can only be decelerated into subsonic by means of shock waves, and if the shock wave is stationary, in our case relative to the tube and if it is perpendicular to the streamlines, it is called static normal shock wave. Theoretical studies and experimental measurements indicate that a shock wave is extremely thin, its thickness is in the order of magnitude of the Maxwellian mean free path of the gas molecule.

The final section of the compression tube is a subsonic diffuser, which has an inlet velocity defined by the outlet speed of the cooling-mixing section, including the static normal shock wave in the supersonic case. At the design of this section of the compression tube, those considerations which generally need to be applied at the calculation of normal subsonic diffuser have to be made.

The Systems of the Compression Tube

The operation of the compression tube basically consists of appropriate interaction of two flows: the flow of the gas to be compressed, which is usually a working medium of a thermal engine cycle, and the flow of the cooling-mixing substance, which is usually water or water vapor. These two flows meet each other in the cooling-mixing section of the compression tube, where generally gas and water-vapor mixture develops.

There are different possible histories for this mixture. The most obvious case when the mixture is released to the ambient atmosphere as it is. It means that both cycles, the cycle of the working fluidum of the thermal machines as well as the cycle of the cooling medium are open ones. The opposite, rather theoretical case when both cycles are closed, e. g. externally heated gas turbine cycle with cooling water regain. The cycles of the internal combustion engines and the gas turbines are very rarely closed, but the cooling substance regain can be a requirement to be met by the compression tube systems. The method of the cooling-mixing water regain and the technical means to realize the process depend very much on the type of the power cycle, i. e. the power machine connected to the compression tube and on the other conditions, e.g. limits to the water supply. The cooling-mixing substance mass flow rate is appr. one tenth of that of the working medium in case of water cooling and at 450 – 500°C exhaustion temperature. The economy of the cooling substance regain is to be calculated occasionally, and it depends on many factors, e. g. on the availability of the cooling water, separation efficiency, investment costs, incremental power gained by the compression tube, etc.

The separation device is optimal, but to produce saturated conditions for the cooling water injected into the hot gas stream is a necessary, unavoidable condition for providing appropriate jet pump effect by the saturated hot water jet pump. The production of the saturated hot water requires heat available above 150°C. The heat necessary to produce saturated hot water for the saturated hot water jet pump for the cooling–mixing in the compression tube can be provided either by the hot exhaustion gas before cooling, or by external heat resources, e. g. direct firing of fuel(s), or by waste heat use, heat from the compressor cooler in case of the gas turbine, etc. At the calculation of the saturated hot water requirement of a supersonic compression tube, the start-up device also need to be taken into consideration.

The operational water requirement of a supersonic compression tube expressed in mass flow rate is appr. one order of magnitude smaller than of the gas to be compressed (1 to 10 ratio), while the start-up device needs 4 to 8 times greater water mass flow rate for the stare-up saturated hot water jet pump to produce the necessary vacuum for the supersonic flow in the stare-up period [18]. The stare-up saturated hot water jet pump is in operation only for several seconds (1 to 4 seconds), thus, while the mass flow rate is great, the mass injected is relatively small. The saturated water for the start-up requires, if no other options are available, a special storage tank [19]. To provide the supersonic velocity flow at the outlet ejector of saturated hot water jet pump, which is essentially a Laval nozzle, the pressure of the saturated water has to be high enough to provide the critical pressure ratio for the Laval nozzle [20]. The number of the envisaged start-up determines the start-up systems lay-out and the capacities of the various components, e. g. the capacity of the storage tank. The compression tube and the other system components can be conceived as part of the engine/turbine exhaustion stack and even can be delivered as packages for existing plants.

This structural independence of the compression tube is a special advantage for the application of the device for existing thermal machines,

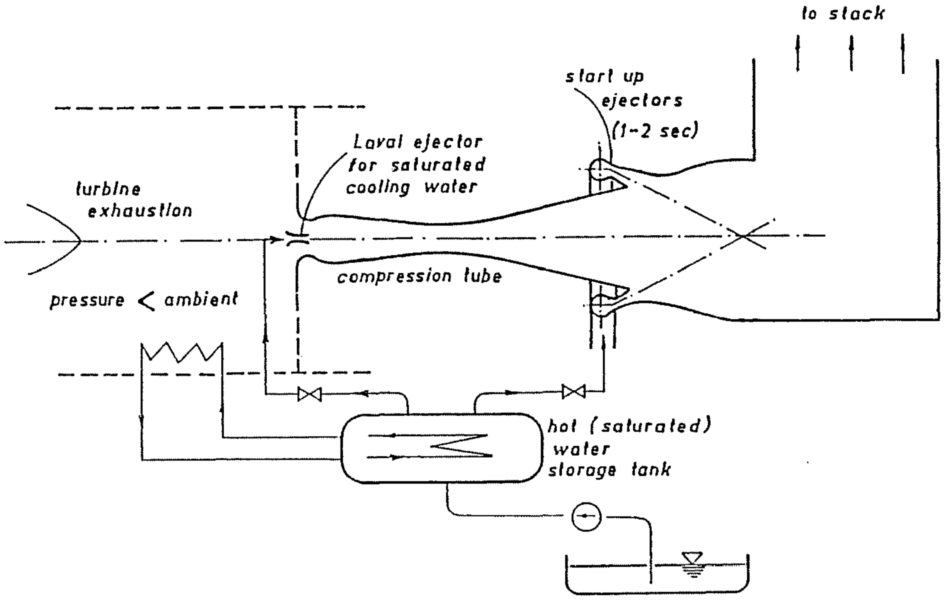

Fig. 1. Compression tube systems

because it can be adjusted to existing engines or turbines without significant modification of the systems (*Fig. 1*).

The systems described above are subject of several pending and granted patents of the authors in many industrialised countries [21].

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