ABSTRACTS

DEPARTMENT OF INTERNAL COMBUSTION ENGINEERING

1. A Theory of Vortex Combustion-Chamber Design, Part I. H. A. Havemann, M.I.Mech.E., V.D.I., *Journal of the Institute of Fuel, London*, December 1953, **26**, No. 155, 294–305.

The cyclone combustion chamber is a new development in the field of combustion apparatus mainly for Gas Turbines but also for steam boilers. Its main objective is to make possible the complete combustion of fuels of low or extremely low rate of combustion. If successful, it would thus allow to use fuels which could not be used for power generation so far.

The cyclone combustion chamber provides means of maintaining for a sufficiently long time either droplets of heavy liquid fuel or particles of pulverized solid fuel in conditions favourable for evaporation and combustion. It provides for a rotating motion of the fuel particles until it has been reduced to very small size due to combustion until combustion is practically completed.

The principle of the chamber was introduced by Lander, and has been developed by different research workers, so that in principle its design follows the following lines:—

Air and droplets are admitted tangentially and enter a vortex type of flow through its periphery, and the combustion gases are extracted axially from the centre. Between periphery and centre combustion takes place, which is started in a primary combustion stage situated in the tangential entry to the chamber proper, where the primary flame is stabilized. There, the fuel particles are wholly or partly ignited, and they complete their combustion in the vortex of the cyclone chamber as far as the mechanics of the vortex allow.

Besides the standard method with tangential entry another version has been recommended, where air is admitted axially, through the primary chamber. Secondary air is led to the periphery of the vortex and made to travel in vortex motion inwards. Droplets issued in the primary zone are thus caught at some radius of the vortex by the secondary air. This radius is called the equilibrium radius.

At the equilibrium radius droplets are held there under the influence of the centrifugal force, P_F acting towards the periphery, and the viscous drag P_A, acting towards the centre of the gas moving in vortex motion towards the centre. For equilibrium both forces are equal $P_A = P_F$ and droplets would rotate at constant radius about the centre under the action of these two forces, with relative motions of the gas. Thus continuously fresh oxygen is supplied for speedy combustion. No random turbulence is created to step up the rate of combustion, and pressure losses should be small.

The shape of the walls of the cyclone chamber is such, that the equilibrium of the droplet is made stable. This means, that any deviation from the equilibrium radius causes forces which lead the droplet back to its equilibrium radius. The restraint thus exerted on the droplet is expressed by "a" and can be varied:

$$\frac{dP_A}{dr} = a\,\frac{dP_P}{dr}.$$

Different shapes of the walls result from the choice of the so-called stability factor "a" their distance L being given by

$$L = B.r^{a(2n+1)-1}$$

where B is a constant, dependent on entrance conditions and particle size, *i.e.*,

$$B = \frac{3k}{8\pi}\,\frac{\eta\rho}{\rho_G(\rho_D - \rho_G)}\,\frac{r_v^{(1-a)(2n+1)}}{K_n^2 x_{max.}^2}$$

where

- k = coefficient of drag
- K_n = constant of tangential gas velocity distribution
- ϵ = normal (dynamic) viscosity of gas
- Q = massflow of gas in unit time
- ρ = mass density, ρ_D for droplet; ρ_G for gas
- r = radius; r_v = radius of the outer vortex; r_i = of the inner radius
- x = particle or droplet diameter.

With the shape of the chamber thus defined, it can be shown that equilibrium conditions are offered to droplets of different sizes, and big droplets will find equilibrium conditions at the periphery, small droplets near the centre of the chamber so that the droplet in the course of its combustion approaches in spiralic motion the centre of the chamber. Since the temperature of the gas in the vortex, and the density, shape, etc. of the droplets are changing the equilibrium conditions become complex, and so is the shape of the walls if predetermined conditions for all phases of combustion should be ensured. It is also necessary to regard the stability of the gas in the vortex, and its inter-connection with the pressure and temperature distribution, and the effect of the gravitational field on the motion of the particle, since, *e.g.*, the action of gravity will make the particle deviate from its circular trajectory if the plane of motion is vertical. Another matter of concern is the right shape for the volute to guarantee smooth transition of the fluid to the vortex proper.

The theoretical treatment in the first part of the publication sets out from the relations given above and assesses the separation of the side walls of the chamber for the conditions of the gas in the vortex expressed by the exponent n, and a value $Z = f(r)$

$$\frac{L}{L_v} = \left(\frac{r}{r_r}\right)^{a(2n+1)-1} \frac{1}{1-\frac{r_i}{r_v}} \left[\frac{Z_i}{Z_v}\frac{r_r - r}{r_r} + \frac{r - r_i}{r_v}\right]$$

It studies the behaviour of the droplets or fuel particles in the vortex in regard to their size distribution, approximately given by the relation

$$\frac{x_{max.}}{x_{min.}} = \left(\frac{T_i}{T_v}\right)^{-\frac{3}{4}} \left(\frac{r_v}{r_i}\right)^{\frac{(1-a)(2n+1)}{2}},$$

and as far as possible, their dynamics and oscillations about the equilibrium radius, and their change of state. The droplet oscillations are expressed by

$$\frac{d^2r}{dt^2} + H\frac{dr}{dt} + J\frac{1}{r^{a(2n+1)}} - K_n^2\frac{1}{r^{2n+1}} = 0,$$

the movement of burning droplets in the vortex occur according to

$$\frac{r}{r_0} = \left(1 - \frac{\lambda t}{x_0^2}\right)^{1/(1-a)(2n+1)}$$

or expressed as a dimensionless velocity function

$$c_{r_0}\frac{x_0^2}{\lambda r_0} = -\frac{1}{(1-a)(2n+1)}\left(1 - \frac{\lambda t}{x_0^2}\right)^{\frac{1}{(1-a)(2n+1)} - 1}.$$

If a change of state of the residues occurs in the vortex the corresponding change of equilibrium radius is given as

$$\frac{r}{r_0} = \left[\frac{x^2(\rho_D - \rho_G)}{x_0^2(\rho_D - \rho_G)_0}\right]^{1/(2n+1)(1-a)} \left[\frac{\nu_0}{\nu}\right]^{1/(2n+1)(1-a)},$$

where ν denotes the viscosity of the gas in the vortex.

Under operating conditions the rate of flow of the gases and their state at entrance will be influenced by external effects, and thus the position of particles will be effected:

$$\frac{r_2}{r_1} = \left(\frac{\eta_1}{\eta_2}\frac{P_1}{P_2}\frac{Q_2}{Q_1}\frac{T_2}{T_1}\right)^{1/(2n+1)(1-a)}$$

with T denoting the gas temperature. Finally, the pressure and temperature distribution in the vortex, as well as the flow pattern is considered and the change in total pressure is found to be

$$\Delta P_{tot} = \rho_G\frac{K_n^2}{2}\left(\frac{1}{r_i^{2n}} - \frac{1}{r_v^{2n}}\right)\left(\frac{1}{n} - 1\right)$$

The distribution of temperature is linked with the size distribution of droplets in the fuel jet, for which the Rosin-Rammler equation is adopted, whereby the fuel volume after a single injection is given by

$$\frac{dR_r}{d\left(\frac{r_0}{r_v}\right)} = \left(\frac{x_{max.}}{\bar{x}}\right)^m \frac{m}{2}(1-a)(2n+1)\left(\frac{r_0}{r_v}\right)^{\frac{m}{2}(1-a)(2n+1)-1} \cdot$$

$$\exp\left[-\left(\frac{x_{max.}}{\bar{x}}\right)^m \left(\frac{r_0}{r_v}\right)^{\frac{m}{2}(1-a)(2n+1)}\right]$$

from which by a method of numerical integration and superposition of all partial volumes of fuel encountered under steady conditions, the distribution of fuel droplets is found.

The trajectory of burning droplets expressed in non-dimensional form is

$$\phi\frac{\lambda}{K_n}\frac{r_v^{n+1}}{x_{max.}^2} = \left(\frac{r_0}{r_r}\right)^{n-a(2n+1)} \frac{1-a}{\frac{n}{2n+1}-a}\left[1-\left(\frac{r}{r_0}\right)^{n-a(2n+1)}\right]$$

From both last mentioned equations the distribution of temperature can be evolved.

The residence time of the fluid in the chamber is

$$t = 2\pi\frac{r_v}{c_{tv}}\,\frac{a(2n+1)}{a(2n+1)+1}\,\frac{1}{\left[\left(\frac{r_{e\phi=0}}{r_v}\right)^{a(2n+1)}-1\right]}\left[1-\left(\frac{r}{r_v}\right)^{a(2n+1)+1}\right].$$

Finally the equilibrium of the gas in the vortex is considered which in the case of a cyclonic combustion chamber will be stable but will tend to become unstable if operating conditions approach those of a gas producer.

2. A Theory of Vortex Combustion-Chamber Design, Part II. H. A. Havemann, *Journal of the Institute of Fuel, London*, January 1954, 27, No. 156, 25–34.

The course of the investigation in the second part turns to a consideration of the entry conditions of the gases which have to ensure that at any point of the periphery of the vortex a predetermined tangential as well as radial air velocity is maintained. The shape of the entrance volute follows from equilibrium conditions for a given droplet—or particle size, for a cyclone chamber with one and more than one entrances. The mean velocity of the flow through any such entrance is considered for even and for a free vortex distribution of the velocity which leads to two different shapes of the entrance volute. Thus for a velocity distribution according to the relation $c_t = K_n/r^n$ the entrance spiral for $a = 0$ is given by

$$\frac{r_{e\phi}}{r_v} = \left\{\left[\left(\frac{r_{e\phi=0}}{r_v}\right)^{a(2n+1)-n} - 1\right]\left(1-\frac{\phi}{2\pi}\right)+1\right\}^{\frac{1}{a(2n+1)-n}}.$$

The design of a vortex combustion chamber is now described accepting a certain massflow of given pressure and temperature, with respect to overall dimensions and wall shape. The maximum and minimum droplet size allowed in the chamber emerge as the most critical factor for the design. The introduction of a relation between the acceleration due to centrifugal action to the acceleration due to gravity allows to limit possible design solutions, since only small deviations of the droplet from its theoretical path can be allowed if touching the walls should be avoided. A design chart is thus evolved which in a graphical way allows to fix the major dimensions. A certain cautionary measure is necessary since all derivations presuppose a constant value of the drag coefficient, and the accuracy of this assumption can finally be checked. If found unjustified a more complex procedure is to be adopted which changes the straight-line relationships (in logarithmically scaled diagrams) to those with curved lines.

The concluding part of the report deals with the conditions of combustion in a vortex chamber as far as they differ from those encountered in usual circumstances. The phenomenon of a continuous relative and varying velocity between particle and gas flows accelerates the physical processes of the transfer of heat and the transfer of matter which are found to depend essentially on the Reynolds number for the relative velocities involved, as do also the chemical processes in the case of combustion. Thus the conditions of burning are to a considerable extent and much more than in the conventional combustion apparatus, a matter of design.

The following conclusions can be drawn as to the advantages of the vortex combustion chamber:

(*a*) All sides of the fuel particle are exposed to the flow of the oxygen carrier, and therefore the limitations due to the transport of matter are greatly reduced and also fresh air is available over a considerable part of the combustion period, thus maintaining the velocity of the chemical reaction.

(*b*) The relative velocity between particle and air is more a matter of choice, according to the knowledge available, than with conventional combustion chambers.

(*c*) The vortex chamber provides sufficient time (i) for drying solid fuel particles which, when dry, move nearer to the combustion zone in the chamber, or may even be disintegrated for the liberation of gases, and (ii) for the combustion of fuels of normally very slow rates of combustion.

Finally, dimensional limitations safeguarding the best possible rate of combustion are outlined, and the problem of ignition is discussed.

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