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A Development of the Fuel Atomizing Device Utilizing High Rotational Speed

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A fuel atomizing device was developed for a combustor of a small gas turbine engine. The device is a rotary atomizer in which liquid fuel is supplied through a stationary nozzle onto a specially shaped disc rotating with a high tangential velocity (over 200 m/sec). The rotary atomizer has shown remarkably good atomization characteristics when used in the engine. The mean droplet size of the atomizer is explained by the following equation for water: $SMD = 0.033 \bullet U^{-0.7} \bullet Q^{0.2} \bullet D^{0.3}$. *The SMD for fuel can be evaluated by the correlation of:* $SMD \propto (\sigma/\rho)^{0.5}$. *The performance together with its configurations will be discussed in detail.*

NOMENCLATURE

SMD	Sauter mean diameter, m
U	peripheral velocity, m/sec (tangential velocity at outer diameter of rotating disc)
D	outer diameter of rotating disc, m
Q	liquid flow rate, m^3/sec
μ	absolute viscosity of liquid, N.sec/m^2
σ	surface tension of liquid, N/m
ρ	liquid density, kg/m^3
δ	liquid film thickness at outer diameter of rotating disc, m
h	liquid film thickness, m
ω	angular velocity, rad/sec
v	liquid velocity, m/sec
r	radius, m
z	coordinate parallel to axis of rotation

INTRODUCTION

It is well known that the size of fuel droplet together with fuel volatility strongly affect the ignition and combustion characteristics as well as emission performance of a combustor. There have been the studies on the evaporation characteristics of a single fuel droplet in an air stream [1]*,[2]. According to these studies, the time required to complete evaporation of a droplet in flowing air depends on various factors such as size of droplet, properties of fuel, air velocity and temperature, etc. However, the major single parameter which affects evaporation time is the droplet size [Fig.1]. The developed atomizer is a type of rotary atomizer, a fuel atomizing device utilizing the centrifugal force of a rotating disc [3],[4]. In a rotary atomizer, it is obviously desirable to utilize a higher tangential velocity for a better quality droplet. It is important to have fuel stretched as thin as possible on the surface of rotating disc before it commences to break down further by air reaction.

Fig.2 illustrates some typical examples of rotary atomizers used in gas turbine engines [5]. However, the developed atomizer is a type in which liquid fuel is injected from a stationary nozzle onto a rotating disc. The tangential velocity of more than 200 m/sec is effectively used in atomizing fuel in the case of this rotary atomizer, compared to the normal speed of about 20 m/sec commonly used for this type of rotary atomizer. This paper will discuss the configuration and the characteristics of the developed rotary atomizer, together with some factors relative to its application in an automotive gas turbine engine.

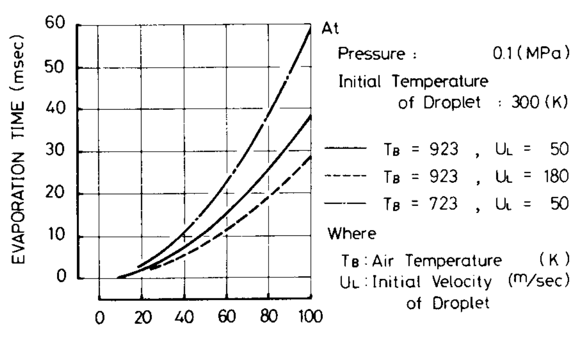

Fig.1 Effect of droplet size on evaporation (after equations by Enzaki et.al [1])

* Numbers in blankets refer to the list of References at the end of the paper.

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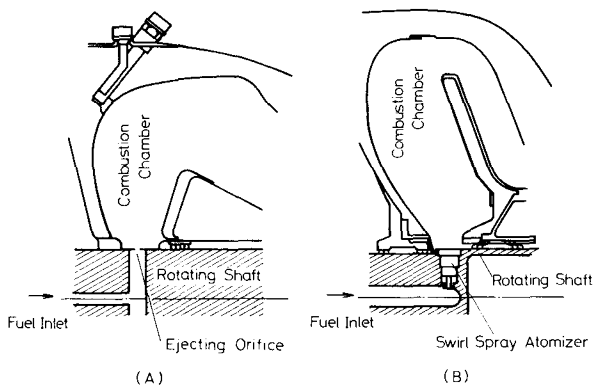


Fig.2 Examples of rotary atomizers in gas turbine engine

PRELIMINARY STUDIES

In a rotary atomizer of the type in which fuel is injected onto a rotating disc, the tangential velocity at the point of the disc where fuel is injected, plays an important role for atomization characteristics. If a given design condition would permit the fuel to be supplied at the center of a rotating disc, it would be easier to achieve good atomization. However, when such a design is not possible, as is the general case, the injection point has to be shifted away from the center outwardly, then the effect of tangential velocity of a rotating disc must be considered.

If fuel is injected onto a part of the rotating disc having higher tangential velocity than a certain limit, part of the fuel splashes away from the rotating disc, instead of spreading outwardly along the disc to give good atomization. These phenomena were studied experimentally with water as shown in Fig.3. The study investigated the effects of such parameters as liquid flow rate, the dimensions of disc and nozzle, the injection angle, distance of disc from nozzle, and roughness of disc surface.

The results of the testing are summarized in Fig.3. Shown are the limits in tangential velocity beyond which part of the liquid is splashed away from the rotating disc and satisfactory atomization is not obtainable. Satisfactory performance as an atomizer can be expected only for the range lower than the velocity limit shown. The tangential velocity of the rotating disc corresponding to this limit is called "the adhesion velocity". The adhesion velocity tends to increase as water velocity increases for the range where the velocity is low. A maximum adhesion velocity is reached for a given condition. The maximum adhesion velocity varies depending on the conditions; however, most of the data lie between 40~60 m/sec of the velocity shown in Fig.3. The principal characteristics of the maximum adhesion velocity for fuel will not change significantly from the data obtained for water. Diesel fuel (type 2-D (JIS)), for instance, indicated a similar level of the maximum adhesion velocity. Considering the wide range of fuel flow rate required, the tangential velocity of the rotating disc applicable to a fuel atomizer is limited to the order of 30~50 m/sec at most in this type of atomizer. To be safe, the velocity should be kept below 20 m/sec as indicated in Fig.3.

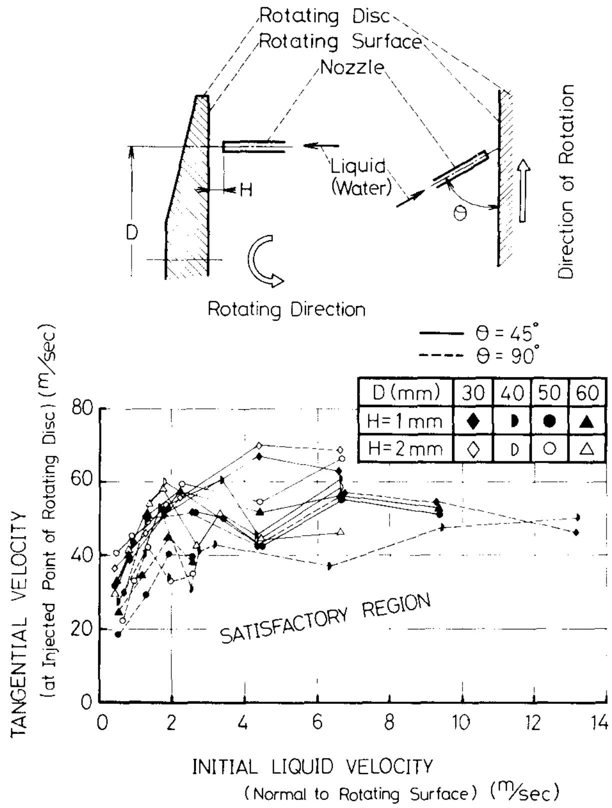


Fig.3 Results of a preliminary study

Thus, it is important to increase the adhesion velocity to realize the good atomization which has been achieved in this study. This is done by using disc configuration illustrated in Fig.4. Fuel is supplied from a stationary nozzle to the inner cylindrical surface of the rotating disc as shown. In this case, fuel is injected to the inner surface of the cylindrical wall where it will stick to the surface due to the centrifugal force acting on the fuel. Various configurations of rotating discs were surveyed in an effort to improve atomization. A conically shaped cylinder, for example, indicated a poor characteristic since a part of fuel injected tended to be splashed out from the conical surface as rotational speed increased. This phenomenon of fuel splashing-out was observed even with as slight a conical angle as six degrees.

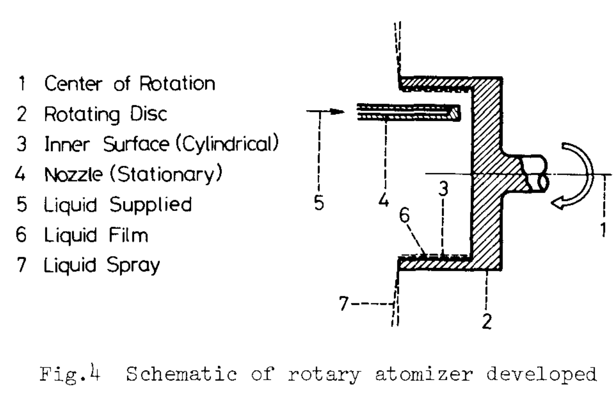


Fig.4 Schematic of rotary atomizer developed

A cylindrically shaped rotating disc where the cylindrical wall is parallel to the axis of rotation, has shown good adhesion of the fuel to the inner surface of the cylindrical wall.

Tests have been conducted to a tangential velocity of over 200 m/sec with satisfactory characteristics.

These are discussed below in more detail.

ROTATING DISC CONFIGURATIONS

Various disc modifications were made to study the effects on atomization on the rotating disc having the cylindrical wall parallel to its axis of rotation. The configurations are shown in Fig.5. The rotating disc shown in (A) has several orifices located close to the brim of the cylindrical wall through which fuel is ejected. The discs marked as (B) and (C) in the figure, have "Plain" and "Stepped" inner surfaces. Fuel is thrown out from the edge of the cylinder wall. Better atomization over a wider range was the purpose of the stepped inner surface-type. A better uniformity of fuel film was expected before leaving the edge by using the step.

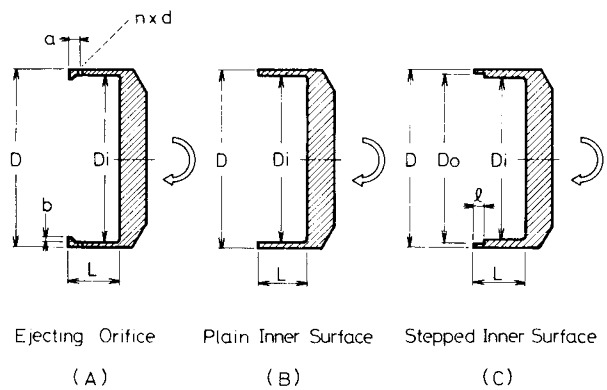


Fig.5 Types of rotating discs investigated

ATOMIZATION CHARACTERISTICS

Test Apparatus

A schematic drawing of the test apparatus is shown in Fig.6. The rotating disc was set at one end of the shaft, which was driven by an air turbine. An air bearing was used to support the shaft, hence the test section was free from oil mist.

Tests were conducted with water (σ=0.0724, μ=0.0010, ρ=1000) for rotating discs of the various diameters between 0.04 and 0.073 m. The flow rate was varied from 1×10^{-6} to 6×10^{-6} m^3/sec for the tests. Samples of spray were collected on a silicon oil film made on a glass plate. These were photographed to measure the droplet size. Sauter mean diameter (SMD) is used to measure the quality of spray, which is defined as

$$SMD = \Sigma di^3 .ni \;/\; \Sigma di^2 .ni \;,$$

where di denotes the diameter of each droplet and ni the number of droplets of the diameter of di. The measuring section was located at the distance, L of 0.1 m from the outer periphery of rotating disc, because the SMD was observed not to be affected significantly by the distance, when L was varied from 0.04 to 0.12 m.

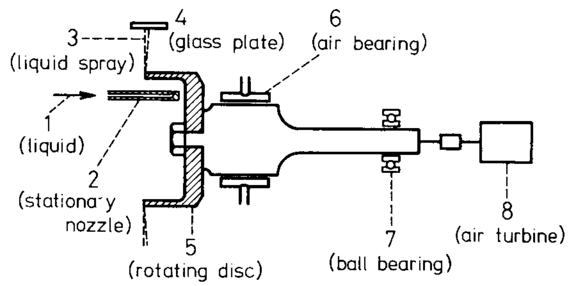


Fig.6 Schematic of test apparatus

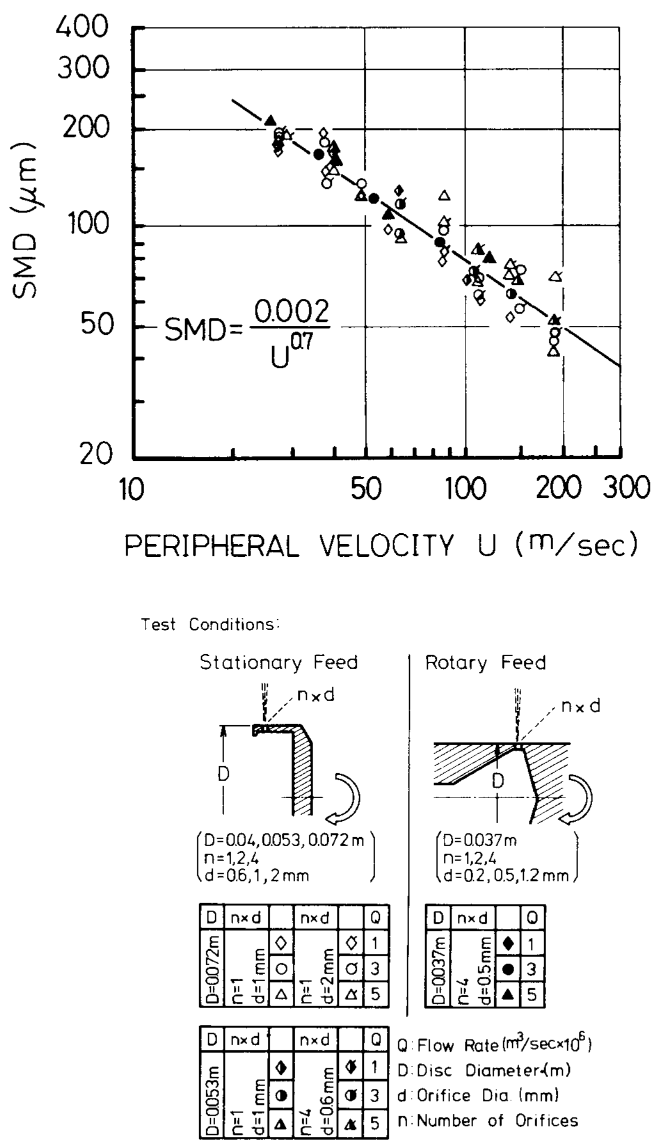


Fig.7 Atomization characteristics
— ejecting orifice–type —

Rotating Disc with Ejecting Orifice

The effect of the ejecting orifices on atomizing characteristics were of prime interest for this rotating disc. Tests were made for the rotating disc by changing the number and also the size of the ejecting orifices. The diameter of the rotating discs were also changed to examine its effect. Both stationary and rotary feed were investigated in these tests. The experimental conditions and the atomization characteristics are summarized in Fig.7. It is seen that there were no differences between the feed systems on atomization characteristics, i.e. the mean diameters are a function of tangential velocity only, measured at the periphery of the rotating discs. The mean diameter of droplets can be expressed by the following equation for water;

$$SMD = \frac{0.002}{U^{0.7}} \tag{1}$$

It is interesting to note that the droplet size is the function of the tangential velocity only, not of the ejecting orifice size. The ejecting orifices were observed not to be filled fully with water for the test conditions described in the above equation.

Rotating Disc of Plain Inner Surface

Since the ejecting orifice size indicated no effect on the atomizing characteristics in the above tests, the rotating disc with no ejecting orifices was of interest because of its simplicity in manufacturing. The rotating disc with plain inner surface, Fig.5 (B), was studied next to determine its atomization characteristics for various disc sizes. The results are shown in Fig.8. It is seen that the tangential velocity of the periphery of the rotating disc is the primary parameter affecting the droplet size, though there are also some effects of both the size of the disc and the water flow rate on the characteristics.

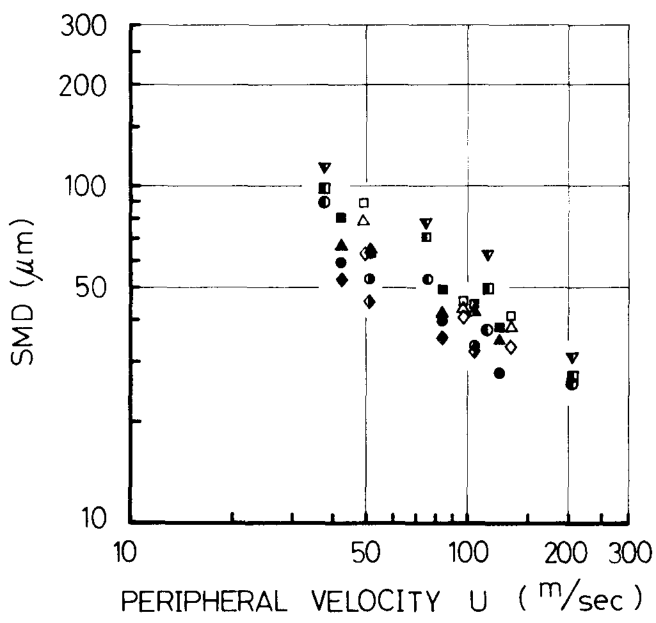


Fig.8 Atomization characteristics
— plain inner surface-type —

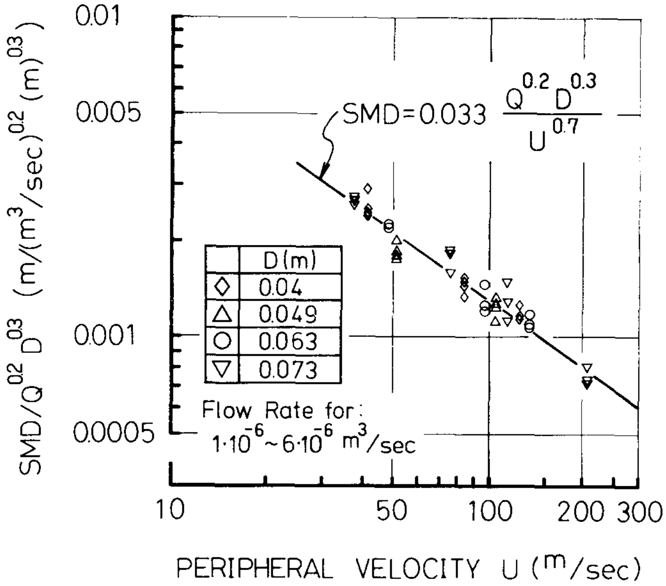
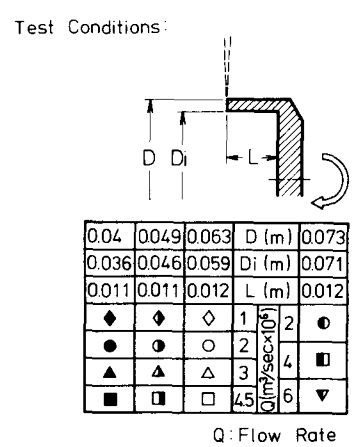


Fig.9 Characteristics of droplet size
— plain inner surface-type —

The effect of these three parameters on the droplet size can be reduced to the following empirical equation.

$$SMD = 0.033\,\frac{Q^{0.2} \cdot D^{0.3}}{U^{0.7}} \tag{2}$$

The accuracy of the empirical equation to the data is shown in Fig.9. The atomizing characteristics of the rotating disc with the stepped inner surface-type, Fig5 (C), were so similar to those of the plain inner surface-type that no distinguising differences were observed.



Droplet Size of Fuel Evaluated

The above experiments were all conducted with water since the technique used in measuring the SMD is generally not applicable for fuels. As the result, the SMD for a specific fuel has to be evaluated before applying the rotary atomizer to a combustion chamber. The study for this purpose is described below.

The liquid film thickness, δ , at the periphery of the rotating disc is considered to be the major factor affecting the SMD, which is obtained by solving the equation of motion using the following assumptions [6],[7];

(1) The dimension of film thickness is small relative to that of the rotating disc.
(2) The flow is viscous, and
(3) radially symmetric.

With the above assumptions, the equation of motion may be reduced to ;

$$\mu \frac{\partial^2 v}{\partial z^2} + \rho r \omega^2 = 0 \qquad (3)$$

Its boundary conditions will be ;

$$v = 0 \quad \text{on wall}$$
$$\frac{\partial v}{\partial z} = 0 \quad \text{at } z=h \text{ (free surface)}$$

With the help of the continuity equation, the above equation can be solved for the film thickness to give;

$$\delta = \left(\frac{6\mu}{\rho} \frac{Q}{\pi D} \frac{1}{D\omega^2} \right)^{1/3} \qquad (4)$$

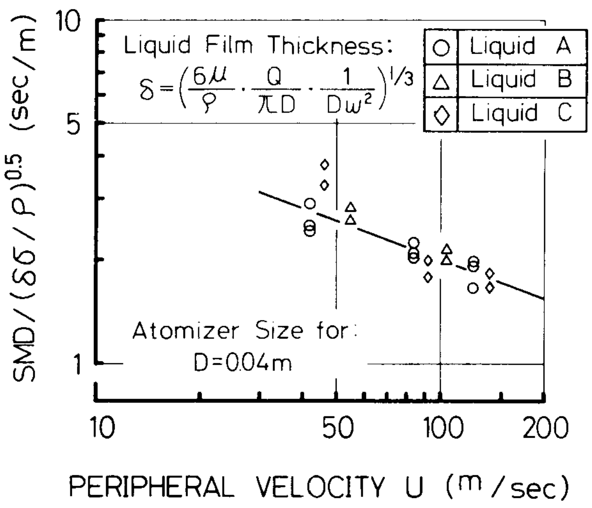


Fig.10 Effect of liquid properties on SMD

Liquid-A: σ=0.0724, μ=0.0010, ρ=1000
Liquid-B: σ=0.026 , μ=0.0025, ρ= 880
Liquid-C: σ=0.0245, μ=0.050 , ρ=1300

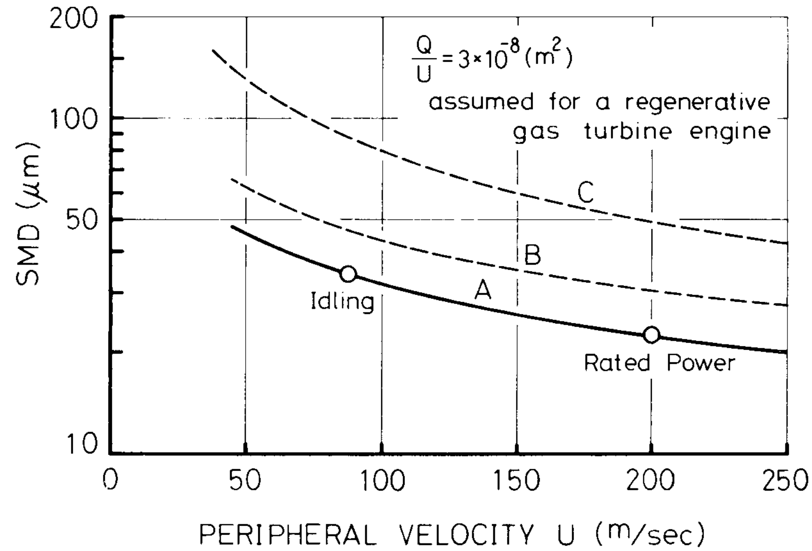


Fig.11 Atomization characteristics evaluated for a combustor

Line A: for diesel fuel with plain inner surface-type
Line B: for water with plain inner surface-type
Line C: for water with ejecting orifice-type

To study the effect of liquid properties on the SMD, a 30% ethyl-alcohol solution in water (liquid-B) and an inorganic solution (liquid-C) as well as water (liquid-A) were studied for their characteristics on droplet size. Liquid-B has properties similar to diesel fuel and liquid-C has a very high viscosity. The results of the tests are shown in Fig.10 together with the details of the liquid properties used.

From the data obtained with these three different liquids, an empirical equation was derived ;

$$\text{SMD} \propto \left(\frac{\sigma}{\rho} \delta \right)^{0.5} \qquad (5)$$

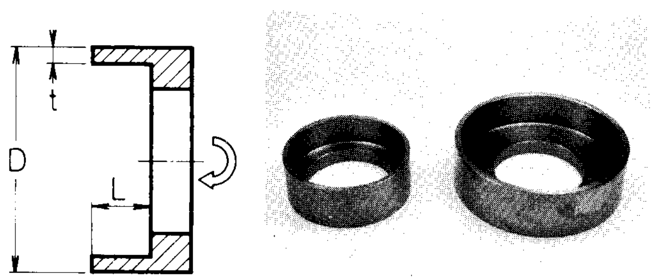
Equation (5), in which the film thickness, δ , was obtained from Equation (4), is less reliable for a liquid with high viscosity since there is some deviation seen in Fig.10 for liquid-C (high viscosity) over the range of low tangential velocity. Equation (5) was used to evaluate SMD for fuel in this study.

The droplet size for a given fuel was studied as shown in Fig.11 before using the rotary atomizer in a combustion chamber for an automotive gas turbine engine. Line A is for a diesel fuel (σ=0.0244, μ=0.00222 and ρ=851) with the rotating disc of the plain inner surface-type. Line A was evaluated by using Equations (2) and (5). The study was made along an operating line chosen for the engine as shown. Line B and line C in Fig.11 are both for water. Line B is for the plain inner surface-type disc, obtained from Equation (2), and line C is the ejecting orifice-type disc, obtained from Equation (1).

It is apparent that the atomization characteristics of the plain inner surface-type, line B, is much superior to line C for the ejecting orifice-type. As line A indicates, the atomizer with a rotating disc of plain inner surface-type is the most promising one for the engine, since the SMD's are less than 35 microns over the whole operating range of the engine.

APPLICATION OF THE ATOMIZER TO A GAS TURBINE ENGINE

The fuel atomizer with the rotating disc of the plain inner surface-type was applied to two different types of gas turbine engines. Both are single shaft regenerative gas turbine engines; the rated outputs are 25 and 55 KW, and their rotating speeds are 86000 and 68000 rpm, respectively. The rotating disc was assembled directly to the shaft in this application and fuel was injected onto the disc from a stationary nozzle. The combustion chamber is a radial-annular type for both engines. A picture of the rotating discs and their specifications are shown in Fig.12. Special care was taken in designing the combustion chamber to protect the rotating disc from heat. Compared to the one with the previously used atomizing system, better ignitability together with improved combustion efficiency for the low speed range resulted with the rotary atomizer as well as a more even temperature distribution at turbine outlet section. The originally used fuel feeding system of the engine is the type shown in Fig.2 (A). In effect this was as a kind of rotating disc with ejecting orifices. The much improved combustor characteristics indicated with the rotary atomizer are understandable since the atomizing characteristics of the ejecting orifice-type are much poorer when compared at the same peripheral velocity as in Fig.11, line C, compared to line A.



	25KW G.T.	55KW G.T.
D (mm)	40	56
L (mm)	10	12
t (mm)	1.5	2

Fig.12 A photo of rotating discs and their specifications for two gas turbine engines

CONCLUSION

A fuel atomizing device using high rotational speed has been developed to improve combustion performance of a gas turbine engine. The device is comprised of a specially shaped rotating disc and stationary nozzle. Fuel is injected from a stationary nozzle onto the rotating disc which effectively uses its peripheral velocity up to almost 200 m/sec to give improved atomization. The atomizing characteristics for various shapes of rotating discs have been discussed in detail to clarify the parameters affecting the performance. The atomizer has been applied to a gas turbine engine to demonstrate the superior characteristics of the fuel atomizer.

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