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2,698,511

METHOD OF OPERATING TURBOJET ENGINES

Filed March 21, 1949

4 Sheets-Sheet 1

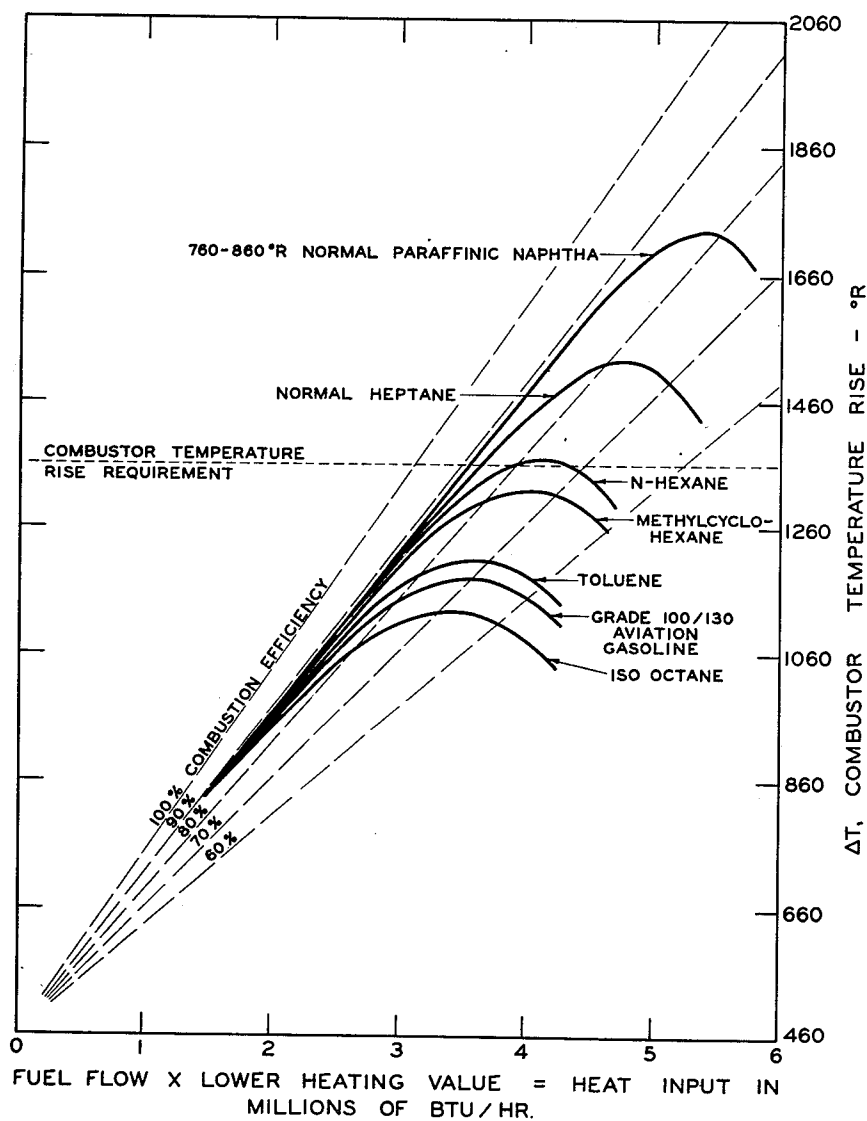


FIG. 1

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4 Sheets-Sheet 2

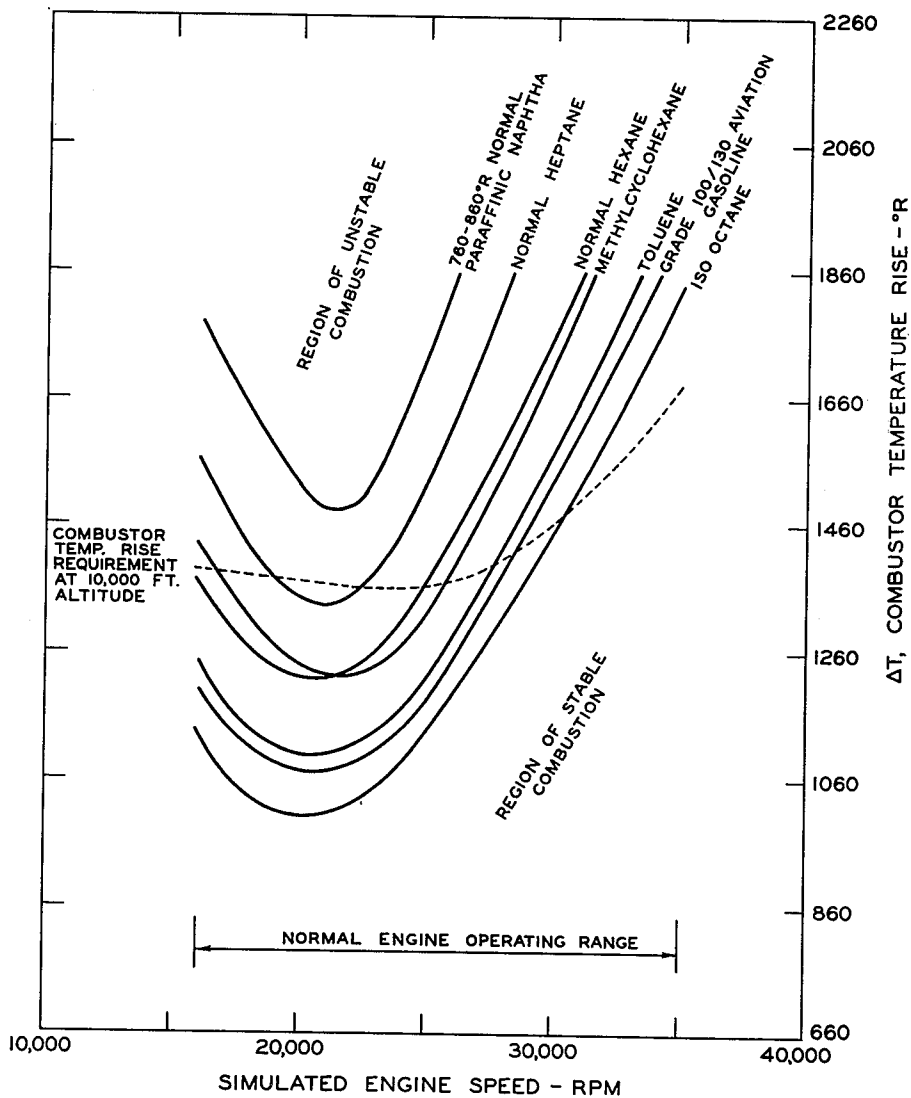


FIG. 2

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4 Sheets-Sheet 3

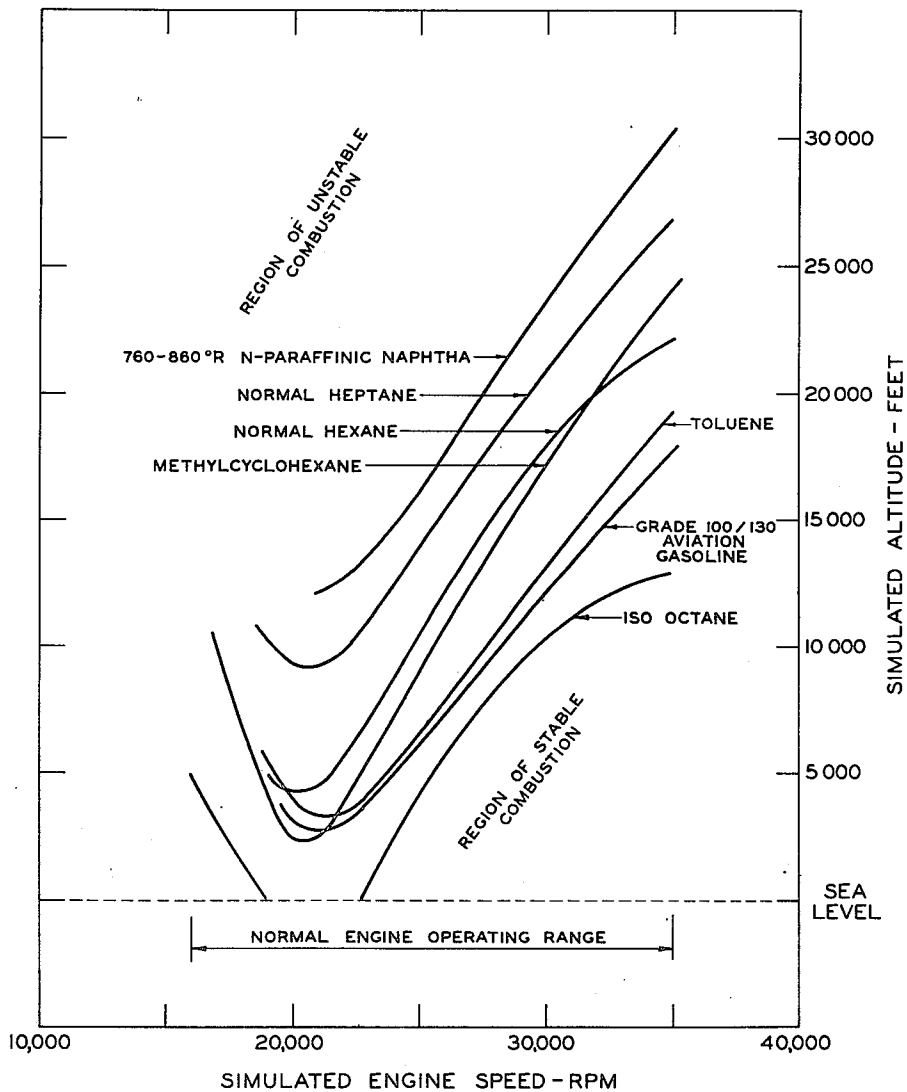


FIG. 3

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4 Sheets-Sheet 4

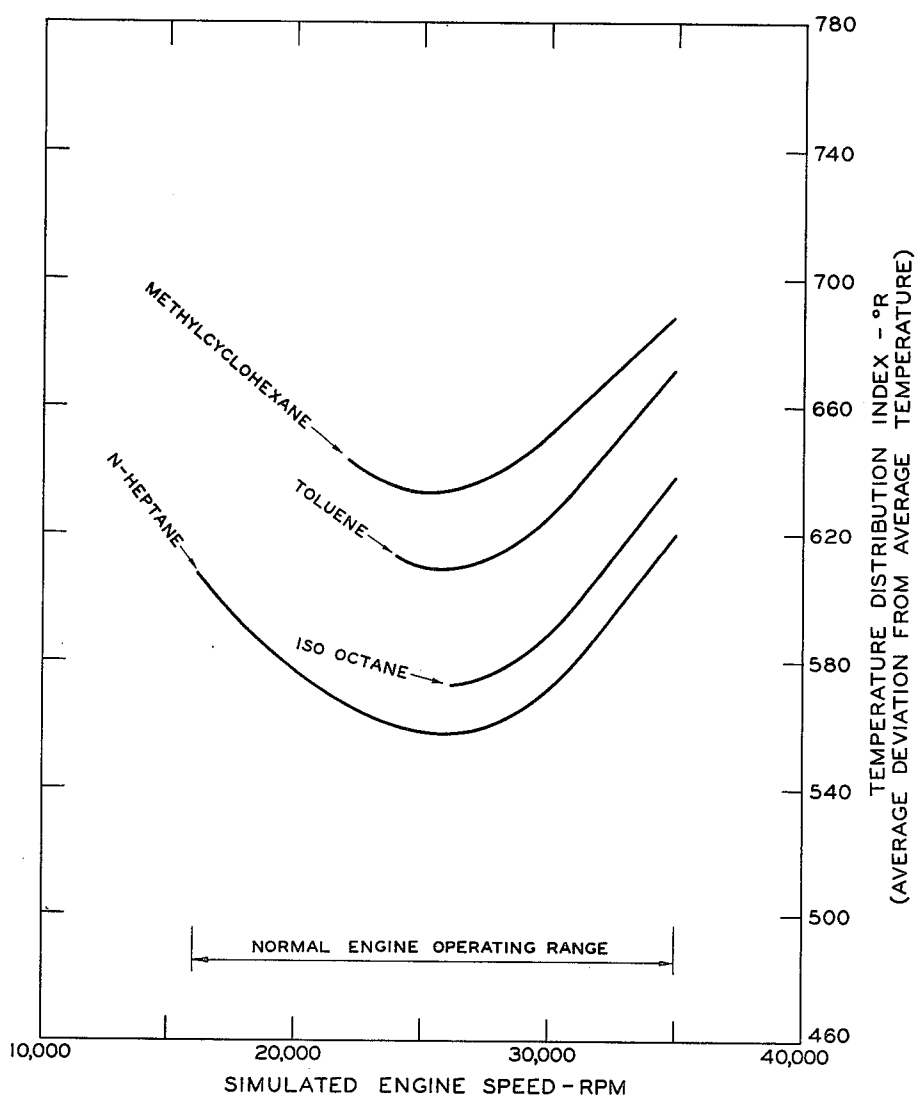


FIG. 4

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2,698,511

METHOD OF OPERATING TURBOJET ENGINES

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12 Claims. (Cl. 60—35.4)

This invention relates to jet engines. In one of its more specific aspects it relates to the operation of continuous flow jet engines. In another of its more specific aspects it relates to the operation of turbo-jet engines.

The gas turbine has presented combustion problems having entirely new and different natures than have been encountered in reciprocating internal combustion engines. The continuous flow combustion process of the gas turbine is aerodynamic as well as thermodynamic in nature. Combustion of fuel within the combustor of a gas turbine is affected by a change of static pressure at the combustor inlet, inlet temperature and inlet velocity. For a particular engine, the combustor air inlet conditions of flow, pressure, and temperature will be determined by the compressor characteristics and the state of the ambient air. The fuel flow rate is generally that which is necessary to maintain the combustor exit temperature required for the particular engine operating condition. Fuel inlet temperature may be varied over a considerable range.

When the gas turbine is applied to aircraft in the form of a turbo-jet engine, one other important element affects combustion of the fuel. As the altitude at which the turbo-jet engine operates is increased, combustion efficiency decreases. Acceleration at the given altitude may cause a failure in operation of the engine because the increase in combustor air velocities more than offsets the beneficial effects of increased combustor inlet air temperatures and pressures.

It was heretofore believed that hydrocarbons do not vary sufficiently in their burning characteristics to make a material difference in the operation of any given jet engine. For that reason, emphasis has been placed on research to determine the design of a jet engine which would have such a structure as would overcome the operational difficulties which are inherently encountered in jet engines. So far, inherent operational difficulties have been only partially overcome by engine design.

A conventional turbo-jet engine comprises three main parts. One of those parts is a compressor. In the compressor, kinetic energy is imparted to the air stream and is transformed in a diffuser into potential energy as measured by an increase in static pressure in the compressor. The second part, a combustor, is provided to receive incoming air and fuel which is burned therein to increase the temperature of the air at substantially constant pressure and resulting combustion gases within the combustor. The third part, a turbine, is ordinarily provided downstream of the combustor and receives gases from the combustion chamber. The gas-turbine unit in the turbine receives the gases from the combustor and develops only enough power to drive the compressor. Forward thrust for the turbo-jet engine is provided by the high-velocity jet of gas which emerges from the turbine.

Performance of a turbo-jet engine is dependent to a large extent upon the "temperature rise" which is obtainable in the engine. "Temperature rise" is that increase in temperature between the inlet to the combustor and the temperature of the gases at the combustor exhaust outlet. The temperature rise must be carefully controlled, however, for the operation of a turbo-jet engine is limited by the ability of the turbine blades to withstand high temperatures. Fuel which is supplied to the combustor is burned in the presence of supplied air and raises the temperature of the combustion gases and unused air by the heat of combustion. An excess of air

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is conventionally utilized to control the temperature of the gases contacting the turbine blades. The hot gases are expanded through the turbine section which provides power for the compressor. Further expansion takes place in a rearwardly extending exhaust nozzle to provide a substantial increase in gas velocity. The thrust which is produced by the engine equals the gas mass flow through the exhaust duct times its increase in speed according to the law of momentum.

A high frequency pulsation phenomenon is commonly encountered in the operation of turbo-jet engines. That high frequency pulsation phenomenon is well known by the term "resonance." "Resonance" indicates pressure or temperature fluctuations within the burning fuel charge and is ordinarily accompanied by a decrease in "combustion efficiency." By "combustion efficiency" I mean the per cent of fuel which is completely burned to produce heat of combustion exclusive of that which is decomposed by the heat of combustion of other portions of the fuel. When resonance occurs and combustion efficiency decreases the temperature rise through the combustor attains a maximum value which is ordinarily less than would be attained at high combustion efficiencies. Usually the flame front tends to fluctuate back and forth in the combustion chamber. As the altitude at which a turbo-jet engine operates is increased, the maximum temperature rise which is obtainable and the fuel-air ratio at which the maximum temperature rise is obtained decreases. The flame front within the combustor tends to fluctuate back and forth. Such movement of the flame front is better known as "cycling." Instability of combustion finally reaches such a state that the flame is extinguished. The point at which combustion will no longer be sustained is known as the "blow-out" or "cut-out." Rich-mixture blow-out is a primary controlling characteristic of turbo-jet engine performance since it defines the maximum thrust output of the engine at a given altitude. When all of the variable operating conditions with a given engine are at their worst, a critical limit will be reached above which combustion will not be maintained. That critical limit is known as a "dead band." Such engines will operate above that dead band because of more favorable conditions of one of the variables.

An object of this invention is to provide an improved method for operating turbo-jet engines. Another object of this invention is to provide a method for extending the operational limits to decrease the dead band for turbo-jet engines. Another object of the invention is to reduce cycling in turbo-jet engines. Another object of the invention is to provide an improved fuel for use in turbo-jet engines. Another object of the invention is to provide a method for obtaining a more uniform temperature distribution pattern of a turbo-jet engine. Another object of the invention is to reduce local overheating of turbine blading and exhaust structures. Other and further objects and advantages will be apparent upon study of the accompanying disclosure and drawings.

Figure 1 is a graph showing the effect of the increasing fuel flow on combustor temperature range with varying hydrocarbon type fuels in a turbo-jet engine at 10,000 feet altitude and 25,000 R. P. M.;

Figure 2 is a graph showing the effect of engine speed on maximum stable combustion temperature rise with various hydrocarbon type fuels in a turbo-jet engine at 10,000 feet altitude; and

Figure 3 is a graph showing the effect of various hydrocarbon type fuels on altitude operational limits of a turbo-jet engine.

The assumption that all hydrocarbons burn with such a standard velocity that the operation of a turbo-jet engine is not materially affected thereby is entirely erroneous. Broadly speaking, this invention resides in the operation of a turbo-jet engine with a fuel which comprises essentially hydrocarbons of which at least 75 per cent by volume is normal paraffins. I have found that by operating a turbo-jet engine with such a normal paraffin fuel many of the inherent operational difficulties of such an engine are greatly reduced or are overcome

to a large extent. The exact reason for this improvement in operation of the turbo-jet engine with a normal paraffin fuel is not known. It is quite possible, however, that much of the improvement is the result of a greater combustion efficiency of the normal paraffin fuel which is used. Part of the improvement is probably the result of less local overheating of turbine blading when operating with normal paraffin fuel.

I have discovered that the best operating results are obtained when operating a turbo-jet engine on a fuel which has a rate of combustion which is explosive. That fuel should also have a high heat release for as the heat release of the fuel within the combustor increases, a greater mass of gas can be heated to a given temperature and thus an increase in thrust per unit of fuel is obtained.

I have discovered that hydrocarbons which are not generally used as fuels for reciprocating internal combustion engines may be used under varying conditions with excellent effect in the operation of turbo-jet engines so as to extend the operational limits of a given engine. Normal paraffins boiling in the range of between 150° F. and 450° F. have the characteristics of high heat release which I have found to be so desirable in turbo-jet engine fuels. More particularly, I have found that better results are obtained in the operation of turbo-jet engines with a normal paraffin fuel which boils in the range of between 200° F. and 400° F. In some instances it may be desirable to provide a fuel having a portion with better start up characteristics than does a larger portion of the fuel but which small portion is not as suitable for the overall operation of the turbo-jet engine. Normal paraffins boiling between 90° F. and 150° F. may be utilized to make up the small portion (not over 10 per cent by volume) of the finished fuel so as to provide improved starting characteristics to the fuel. Normally liquid fuel is injected into the combustor through injection nozzles in such a manner that the fuel stream disintegrates into fine droplets which vaporize to form a combustible mixture.

For the most efficient turbo-jet engine operation, I have found that a fuel comprised essentially of a hydrocarbon stock and which contains between 85 per cent and 100 per cent by volume of normal paraffins boiling within the above designated preferred boiling range is highly superior. A fuel comprising essentially a hydrocarbon stock and containing between 75 per cent and 100 per cent by volume normal paraffins boiling in the range of between 150° F. and 450° F. will also give superior performance.

Olefinic and aromatic materials also have properties of high heat release and rapid combustion which are desirable for the operation of turbo-jet engines. Those materials, however, have the disadvantage of producing carbon laydown which may at times interfere with the operation of the gas turbine. For that reason, it is preferred that if the finished fuel should contain those materials that it be in an amount of not more than 10 or 15 per cent by volume of those materials boiling within the range of between 150° F. and 450° F.

Specific normal paraffins which may be utilized for at least 75 per cent by volume of the hydrocarbon stock of the fuel for a turbo-jet engine may include normal hexane, normal heptane, normal octane and a light naphtha. A small portion of normal pentane may be utilized in the fuel for the purposes of improving starting characteristics of that fuel. Specific olefins which may be utilized to make up a portion of the fuel include diisobutylene. Aromatics such as benzene and toluene and/or substituted aromatics, such as cumene, may be used.

It is preferred that the composite turbo-jet engine fuel contains substantially no isoparaffinic material. In view of the fact that it is practically impossible to eliminate all isoparaffins in commercial distillation systems, it will usually be found necessary to tolerate up to about 10 per cent by volume of isoparaffins in the finished fuel. Other non-deleterious materials may also go to make up a portion of the finished fuel. Some materials which may be utilized with our preferred fuel are nitroparaffins, nitro aromatics, ketones, ethers, and alcohols. Such materials may make up as much as 20 per cent by volume of the finished material. It is preferred, however, to limit those materials to an amount not exceeding 5 per cent by volume of the finished fuel.

Other materials other than the lower boiling normal paraffins may be utilized to impart improved starting characteristics to the turbo-jet fuel which is utilized in

the method of this invention. Starting characteristics and thrust output of a given fuel may be improved by the addition of a small portion of peroxides which may include hydroperoxides having the formula ROOH where R is a hydrocarbon radical and having between two and nine carbon atoms per molecule. Examples of such additives are cumene hydroperoxide, benzoyl hydroperoxide, and ethyl hydroperoxide. The quantity of this type additive which may be advantageously employed may vary from about 0.1 per cent to about 5 per cent by volume of the finished fuel. It is preferred to utilize not more than 3 per cent by volume of the additive in the finished fuel because the relatively small incremental benefits for additives above 3 per cent becomes unconomical.

Starting characteristics and thrust output of a given turbo-jet engine fuel may also be improved by the addition of a small portion of alkyl nitrates or alkyl nitrites having between one and six carbon atoms per molecule. Examples of such additives are amyl nitrate, ethyl nitrate, isoamyl nitrate, isopropyl nitrate, cyclohexyl nitrate, hexyl nitrate or their corresponding nitrites. The quantity of this type additive which may be advantageously employed may vary from about 0.1 per cent to about 5 per cent by volume of the finished fuel. It is once again preferred to limit the quantity of the additive to not more than 3 per cent by volume of additive in the finished fuel because of the relatively small incremental benefit for additions above 3 per cent. Starting characteristics of a given fuel may also be improved by using a mixture of alkyl nitrates and peroxides in a quantity ranging between 0.1 per cent and 5 per cent by volume of the finished fuel.

Turbo-jet engines may be operated when the fuels discussed hereinabove are supplied to a given engine at fuel-air ratios ranging between 0.005 and 0.040. It is within the scope of this invention to operate a turbo-jet engine with the preferred fuel described above and with the injection of oxygen. If oxygen or an oxygen-supplying compound, such as a peroxide, is used for the purpose of supplying oxygen rather than air, the fuel-air ratios would necessarily have to be adjusted accordingly so as to maintain a fuel-oxygen ratio equivalent to the fuel-air ratio disclosed herein. It is preferred to operate a turbo-jet engine by supplying the above described fuel to the engine at a fuel-air ratio ranging between 0.01 and 0.03. Air is supplied to the turbo-jet engine at an inlet air pressure of between 0.2 and 8 atmospheres at a Mach number ranging between 0.01 and 0.80. "Mach number" is defined as the ratio of the velocity of a gas to the local velocity of sound in the gas. The preferred inlet air pressure ranges between 0.5 and 4 atmospheres at a Mach number ranging between 0.02 and 0.30. Fuel is supplied to the combustor at a temperature ranging between -60° F. and 240° F. and preferably at a temperature ranging between 40° F. and 100° F. Air which is supplied to the combustor is preferably supplied at a temperature between -30° F. and 740° F. and preferably at a temperature between 40° F. and 440° F. When operating a turbo-jet engine within the above range of conditions the normally paraffinic fuel utilized in this invention burns within a combustion efficiency range of between 40 per cent and 100 per cent, and ordinarily within the range of from 85 per cent to 100 per cent. The exact fuel-air ratio which is utilized is dependent upon engine design limitations, such as turbine durability. Fuel injection temperatures are dependent on fuel characteristics, such as freezing point and volatility characteristics, as well as upon injection nozzle characteristics.

As pointed out above, emphasis has heretofore been directed to the design of turbo-jet engines so as to overcome the inherent combustion problems of conventional engines. I do not agree with the conclusions which have been maintained heretofore that all hydrocarbon fuels have such standard combustion characteristics that no great difference is obtained in the operation of a turbo-jet engine when utilizing any one of those fuels. In order to demonstrate the accuracy of my own conclusions, I have made comparative runs of a combustor of a turbo-jet engine while varying certain individual variables which are known to affect combustion of fuel in turbo-jet engines. The comparative runs of a combustor were made with normal heptane, isooctane (2,2,4 trimethylpentane), methylcyclohexane, toluene, normal

hexane, and a 300° F.-400° F. normal paraffinic naphtha, chemical and physical properties of which are set forth in Table I below. Grade 100/130 aviation gasoline, which is conventionally used as a turbo-jet engine fuel, was also utilized in the comparative runs.

TABLE I

Chemical and physical properties of test fuels

Identification Number	Normal Heptane Average	Isooctane Average	Methylcyclohexane	Toluene	N-Hexane	Normal Paraffinic Naphtha
ASTM Number.....	0.7	99.5	79.3	108.6 (0.91 ml. TEL)	52.5	-9.2
Specific Gravity, 60F/60F.....	0.6840	0.6922	0.7703	0.8644	0.6843	0.7617
Refractive Index, D/20.....	1.3878	1.3916	1.4256	1.4945	1.3852	1.4274
Aniline Point, F.....	157.2	176.3	95.0	-----	137.1	151.5
Freezing Point, F.....	-131.57	-166.66	-----	-----	-----	-----
Molal Purity, Percent.....	99.06	99.12	177.5	98.23	-----	-----
Kinematic Viscosity:						
cs. at 32F.....	0.75	0.92	1.09	0.88	0.62	1.74
cs. at 100F.....	0.53	0.62	0.70	0.58	0.45	1.00
cs. at 130F.....	0.46	0.54	0.60	0.50	0.40	0.83
ASTM Distillation, F.:						
IBP.....	204	205	209	223	151	313
5%.....	205	207	211	225	153	325
10%.....	206	207	211	227	153	328
50%.....	206	207	211	227	153	347
90%.....	207	208	212	228	155	377
DP.....	207	208	213	228	155	395

¹ 77.5% methylcyclohexane, 3.6% 2,2,5 dimethylhexane, 12.1% toluene, 1.0% 1,2 dimethylpentane, 3.9% ethylcyclopentane, 1.9% normal heptane.

The effect of fuel flow on the maximum obtainable combustor temperature rise was determined by the utilization of the six fuels listed above in a given combustor. The results of those operations are graphically set forth in Figure 1 of the drawings. The curve for grade 100/130 aviation gasoline is also included on this table. That graph shows the effect of increasing fuel flow upon the combustor temperature rise with various hydrocarbon type fuels in a conventional combustor under conditions which are obtained at 10,000 feet altitude and at 25,000 R. P. M. The combustor temperature rise which was obtained in the operation of the combustor with the 300-400° F. normal paraffinic naphtha and with normal heptane far exceeded that which was obtained in the operation of the combustor with the other five fuels.

The same fuels were utilized in the operation of the same combustor to determine the effect of changing engine speeds upon the combustor temperature rise. The effect of engine speed on the maximum stable combustor temperature rise with the various hydrocarbon type fuels in the combustor at conditions which are encountered at 10,000 feet altitude are graphically disclosed as Figure 2 of the drawing. Once again the normal paraffinic naphtha and the normal heptane produce results which far surpass the other fuels in maintaining the maximum combustor temperature rise.

The superiority of the normal paraffinic naphtha and normal heptane in the operation of a combustor at conditions of varying altitude is graphically set forth in Figure 3 of the drawing.

Four fuels were utilized to operate the combustor to determine the effect of engine speed on combustor discharge temperature patterned at conditions which are encountered at 5,000 feet altitude. Methylcyclohexane, toluene, isooctane, and normal heptane were the fuels utilized in those operations. Normal heptane proved to have the least deviation from average temperature of the four fuels as shown in Figure 4 of the drawing.

As shown in Figures 1 and 2 of the drawing, only the 300-400° F. normal paraffinic naphtha and the normal heptane fuel, which fall within the fuel boiling range of this invention, extended the rich mixture operation of the turbo-jet combustor to points above the combustor temperature rise requirement to such an extent that the operational limitations are substantially extended thereby. The normally paraffinic fuels which fall within my preferred boiling range increase the "dead band" or operational limit when each individual variable was varied. It is clear therefore that the operational limit of a given turbo-jet engine is increased by its operation with the method of this invention.

The specific normal paraffinic fuels which were utilized in the comparative runs of the turbo-jet combustor are merely exemplary of the normal paraffins which are dis-

closed as fuels for the operation of turbo-jet engines in the manner disclosed in this invention. As will be evident to those skilled in the art, various modifications of the invention can be made or followed by blending normal paraffin fuels in the light of the foregoing disclosure and

discussion without departing from the spirit or scope of the disclosure.

I claim:

1. An improved method for operating a turbo-jet engine which comprises continuously injecting into a combustor chamber a fuel consisting essentially of a hydrocarbon stock and containing less than 10 per cent by volume isoparaffins and at least 75 per cent by volume normal paraffins boiling in the range of between 150° F. and 450° F. at a temperature between -60° F. and 240° F.; passing air into an air compressor; injecting the resulting compressed air into the forward end portion of said combustor chamber at a velocity Mach number between 0.01 and 0.80, at a pressure of between 0.2 and 8 atmospheres, at a temperature between -30° F. and 740° F., and at a fuel-air ratio between 0.005 and 0.040; burning said fuel in said combustor chamber at a combustion efficiency within the range of from 40 per cent to 100 per cent so as to heat said air and resulting combustion gases; exhausting said gases through a turbine and out of a rearwardly extending exhaust duct at an exit velocity higher than the flying speed of said engine; and utilizing the power developed by said turbine to drive said air compressor.

2. The method of claim 1, wherein said normal paraffins boil between 200° F. and 400° F.; and injecting said fuel into said combustor chamber at a fuel-air ratio between 0.01 and 0.03.

3. The method of claim 1, wherein said normal paraffins consist of 300°-400° F. normal paraffinic naphtha; and injecting said fuel into said combustor chamber at a fuel-air ratio between 0.01 and 0.03.

4. The method of claim 1, wherein said normal paraffins consist of normal heptane; and injecting said fuel into said combustor chamber at a fuel-air ratio between 0.01 and 0.03.

5. An improved method for operating a turbo-jet engine which comprises continuously injecting into a combustor chamber a fuel consisting essentially of a hydrocarbon stock and containing substantially no isoparaffins and at least 75 per cent by volume normal paraffins boiling in the range of between 150° F. and 450° F., together with from 0.1 per cent to 5 per cent by volume of additive materials selected from the group consisting of alkyl hydroperoxides, aryl hydroperoxides, alkyl nitrates and alkyl nitrites at a temperature between -60° F. and 240° F.; passing air into an air compressor; injecting the resulting compressed air into the forward portion of said combustor chamber at a velocity Mach number between 0.01 and 0.80, at a pressure of between 0.2 and 8 atmospheres, at a temperature of between -30° F. and 740° F., and at a fuel-air ratio between 0.005 and 0.040; burning said fuel in said combustor chamber at a combustion efficiency within the range of from 40 per cent to 100 per cent so as to heat said air and resulting com-

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bustion gases; exhausting said gases through a turbine and out of a rearwardly extending exhaust duct at an exit velocity higher than the flying speed of said engine; and utilizing the power developed by said turbine to drive said air compressor.

6. The method of claim 1, wherein said air is injected into said combustor chamber at a velocity Mach number between 0.02 and 0.30, at a pressure between 0.5 and 4 atmospheres, at a temperature between 40° F. and 440° F., at a fuel-air ratio between 0.01 and 0.03; and said fuel is burned at a combustion efficiency within the range of from 85 per cent to 100 per cent.

7. The method of claim 5 wherein said additive materials are alkyl hydroperoxides.

8. The method of claim 5 wherein said additive materials are aryl hydroperoxides.

9. The method of claim 5 wherein said additive materials are alkyl nitrates.

10. The method of claim 5 wherein said additive materials are alkyl nitrites.

11. An improved method for operating a turbo-jet engine which comprises continuously injecting into a combustor chamber a fuel consisting essentially of a hydrocarbon stock and containing substantially no isoparaffins and at least 75 per cent by volume normal paraffins boiling in the range of between 150° F. and 450° F., together with from 0.1 per cent to 5 per cent by volume hydroperoxides having the formula ROOH where R is a hydrocarbon radical and having between 2 and 9 carbon atoms per molecule at a temperature between -60° F. and 240° F.; passing air into an air compressor; injecting the resulting compressed air into the forward portion of said combustor chamber at a velocity Mach number between 0.01 and 0.80, at a pressure of between 0.2 and 8 atmospheres, at a temperature of between -30° F. and 740° F., and at a fuel-air ratio between 0.005 and 0.040; burning said fuel in said combustor chamber at a combustion efficiency within the range of from 40 per cent to

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100 per cent so as to heat said air and resulting combustion gases; exhausting said gases through a turbine and out of a rearwardly extending exhaust duct at an exit velocity higher than the flying speed of said engine; and utilizing the power developed by said turbine to drive said air compressor.

12. The method of claim 1, wherein said fuel contains normal paraffins boiling between 90° F. and 150° F. and in an amount not exceeding 10 per cent by volume.

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