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EXPERIMENTAL STUDY ON THE STABILITY OF PREMIXED FLAME USING CONICAL STABILIZER

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ABSTRACT

The aim of the present work is to study and test flame stability and blow off for natural gas by use two design for conical stabilizer to enhance the swirl phenomena through the combustion. An experimental test rig is used to study the effect of the two designs of conical stabilizer on flame stability. In the present work flame stabilization using conical stabilizer is investigated to study the flame stability limits for a free jet premixed flame burner. The stability limit (blow off) is examined through changing some parameters in particular of the inclination angle of exit jet of conical stabilizer. The effect of these parameters on the flame stability discussed. The measurements of experiment is mainly depends on visualization. So that an experimental test rig is constructed to fulfill these objectives and different measurements are recorded and analyzed. The study showed that the conical stabilizer has improved the flame stability extend of free flame. The conical stabilizer case I has an effect on the stability limit more than on the conical stabilizer case II. The exit jet with angle on vertical axis for higher velocities of the premixed mixture.

إن الهدف من هذا العمل هو دراسة واختبار استقرار اللهب وحد الإنطفاء للغاز الطبيعي عن طريق استخدام تصميمين لمثبت مخروطي لتعزيز ظاهرة الدوامات من خلال الاحتراق. لقد شيدت منصة اختبار لدراسة تأثير للتصاميم المخروطية على استقرار اللهب. يقدم العمل الحالي دراسة لمثبت اللهب المخروطي من حيث حد الاستقرار لموقد اللهب الحر. يتم فحص حد الاستقرار (حد الإنطفاء) من خلال تغيير بعض الخصائص على وجه الخصوص زاوية ميل الباثق. لقد تم مناقشة تأثير هذه المعايير على استقرار اللهب. لقد إعتمدت القياسات أساسا على التصوير. تم إنشاء منصة الاختبار لتحقيق هذه الأهداف ويتم تسجيل القياسات المختلفة وتحليلها. وأظهرت الدراسة أن حد الاستقرار قد تحسن. كما أن حد الاستقرار لمثبت اللهب المخروطي رقم ١ لديه تأثير أفضل من ٢. باثق الخروج مع زاوية على محور عمودي لأعلى السرعات للخليط.

Keywords: conical stabilizer, Flame stability, Blow off

1. INTRODUCTION

Flame stability is a topic of major interest, because many practical devices from domestic boilers to gas turbine combustors experience thermo-acoustic instabilities. Much of the current research has concerned low emission systems operating in the lean premixed mode, in which the flame is less well stabilized and more sensitive to external perturbations. In many systems, the flame is anchored by hot recirculating gases. In some cases, these gases form the core of a swirling flow generated by an aerodynamic injector. In other situations hot products recirculate in the wake of a bluff-body. The stabilized flame takes an inverted conical shape, and the flame-front is subjected to wrinkling and straining by large scale eddies. The flame tip moves freely in the flow field and it is therefore more susceptible to acoustic perturbations.

Radhakrishnan et al. [1] had performed an experimental work on a constant cross-sectional area tubular combustor. The primary variables varied were the reference velocity, mixture temperature and the length over which the fuel and air were allowed to mix. The aim of varying the premixing length was to study the effects of small-scale concentration non-uniformities on the lean ignition and blow off limits. It was mentioned that the length of the recirculation zone downstream of a flame holder is a more appropriate length scale for defining the flame stability characteristics than its geometric size, although the latter is a more easily measurable quantity.

Gil et al. [2] have studied experimentally the flame stabilization and flow field characteristics of premixed flames in an axisymmetric curved-wall jet burner. Results showed that the blow off velocity is much higher and the flame height is reduced significantly as compared with the tube jet burner. It is noticed that the condition of maximum blow off velocity occurs when the mixture is rich and the equivalence ratio increases as the nozzle exit area decreases.

An experimental study concerned with the characteristics of a free non premixed flame El-Mahalawy et al. [3] investigated the stability characteristics of free diffusion flames produced by the injection of gaseous fuel into the center of a reverse flow zone formed by a bluff body placed in the air stream at a burner mouth. The results show the diminished effect of the cone angle of the bluff body on the extinction values. This result leaves the area blocked to be the solely dominant geometrical factor affecting the stability performance.

Schefer [4] has studied the stability characteristics of a premixed, swirl-stabilized flame to determine the effects of hydrogen addition on flame stability under fuel lean conditions. The results showed that as the lean stability limit was approached the overall OH mole fraction decreased, the flame width decreased and flame length increased. For the operating conditions near the lean stability limit, the addition of a moderated amount of hydrogen to the methane/air mixture resulted in a significant increase in the OH concentration and a more robust appearing flame.

Prakash et al. [5] have described a method for detecting and preventing lean blowout in a premixed swirl stabilized combustor. The result showed that splitting the total fuel between a swirling, premixed annual port and a central premixed pilot in increasing pilot fractions could improve safety margin by shifting $\Phi_{\text{lean blowout}}$ to leaner values

Benoit Bedat et al.[6] study The stabilization limits of v-flame and conical flames are investigated in normal gravity (+ g) and reversed gravity (upside-down burner, - g) to compare with observations of flame stabilization during microgravity experiments. The results show that buoyancy has the most influence on the stabilization of laminar v -flames. Under turbulent conditions, the effects are less significant. For conical flames stabilized with a ring, the stabilization domain of the +g and -g cases are not significantly different. Under reversed gravity, both laminar v-flames and conical flames show flame behaviors that were also found in microgravity. The v-flames reattached to the rim and the conical flame assumed a top-hat shape.

Byung-il Choi et al.[7] the study experimentally and numerically the combustion stability of the combustor with Methane gas which used as a fuel instead of liquefied fuel for convenience. The combustion stability of the combustor was measured, and the flame shapes were visualized experimentally. Numerical simulations were performed to examine the details of the flame structure and flame stabilization mechanism inside the micro-cyclone combustor. The mixing and flow characteristics of non-reacting and reacting flows in the combustor were examined using the simulation results. The mixing of the fuel with air in a non-reacting flow field was enhanced by increasing the equivalence ratio for a fixed fuel flow rate. For non-reacting flow, a recirculation region and a small negative axial velocity region near the injection ports were formed. The recirculation region became wider with decreasing equivalence ratios. For reacting flows, however, the recirculation region disappeared and the only small negative axial velocity region was formed near the fuel injection ports. The flame was stabilized inside the combustor because the flame base was anchored near the negative axial velocity region near the fuel injection ports.

Mohy S. Mansour [8] the stability characteristics of partially premixed turbulent lifted methane flames have been investigated. Mixture fraction and reaction zone behavior have been measured using a combined 2-D technique of simultaneous Rayleigh scattering, Laser Induced Predissociation Fluorescence (LIPF) of OH and Laser Induced Fluorescence (LIF) of C_2H_x. The data show that the mixture fraction field on approaching the stabilization region was uniquely characterized by a certain level of mean and rms fluctuations. That suggests that the stabilization mechanism was likely to be controlled by premixed flame propagation at the stabilization region. Triple flame structure had been detected in the present flames, which was likely to be the appropriate model at the stabilization point.

V.R. Katta et al.[9] They made a designed of center body burner of understanding the coupled processes of formation, growth, and burn-off of soot through decoupling them using recirculation zones (RZs). Experimentally it was found that the sooting characteristics of the center body burner could be altered dramatically via simple changes in the operating conditions. One of the interesting operating regimes in which a flame lifts off and forms a column of soot was identified when oxygen in the annulus air jet was reduced sufficiently. Soot that was transported into the RZs was found to have a significant effect on the flame lift-off height. Numerical experiments were performed to aid the understanding of the relationship between soot and flame lift-off. Radiation from the soot decreases the temperature, slows the autoignition process, and increases the lift-off height. Soot oxidation consumes O and OH radicals, slows the autoignition reactions, and increases the lift-off height.

Kushal S. Kedia et al.[10] investigated the flame stabilization mechanism and the conditions leading to the blowoff of a laminar premixed flame anchored downstream of a heat-conducting perforated-plate/ multi-hole burner, with overall nearly adiabatic conditions, unsteady, fully resolved, two dimensional simulations with detailed chemical kinetics and species transport for methane-air combustion. Results showed a bell-shaped flame stabilizing above the burner plate hole, with a U-shaped section anchored between neighboring holes. The base of the positively curved U-shaped section of the flame was positioned near the stagnation point, at a location where the flame displacement speed was equal to the flow speed. That location was determined by the combined effect of heat loss and flame stretch on the flame displacement speed. As the mass flow rate of the reactants wass increased, the flame displacement speed at that location varies non-monotonically. As the inlet velocity was increased, the recirculation zone grows slowly, the flame moves downstream, and the heat loss to the burner decreases, strengthening the flame and increasing its displacement speed. While the heat loss decreases, the higher flame curvature dominates thereby reducing the displacement speed of the flame base. For a stable flame, the gradient of the flame base displacement speed normal to the flame was higher than the gradient of the flow speed along the same direction, leading to dynamic stability. As inlet velocity was raised further, the former decreases while the latter increases until the stability condition was violated, leading to blow off. The flame speed during blow off was determined by the feedback between the growing recirculation zone and the cooling burner plate.

The aim of the present work is to study and test a conical stabilizer for flame stability to enhance the swirl phenomena through combustion gases. The measurements of experiment is mainly depends on visualization.

Experimental test facility:
The study is to investigate experimentally the effect of the conical stabilizer exit jet angle on the flame stability of the premixed gaseous. To accomplish the above needs, a test rig is designed and manufactured here to carry out the experiments using the suitable instrumentation.

The test rig used in the present study is shown schematically in Fig. 1. The experimental facility was designed to generate data to study flame stability and blow off limits for premixed fuel-air mixtures. The test rig is made up of a burner with controlled air and fuel supply systems, as well as the measuring devices.

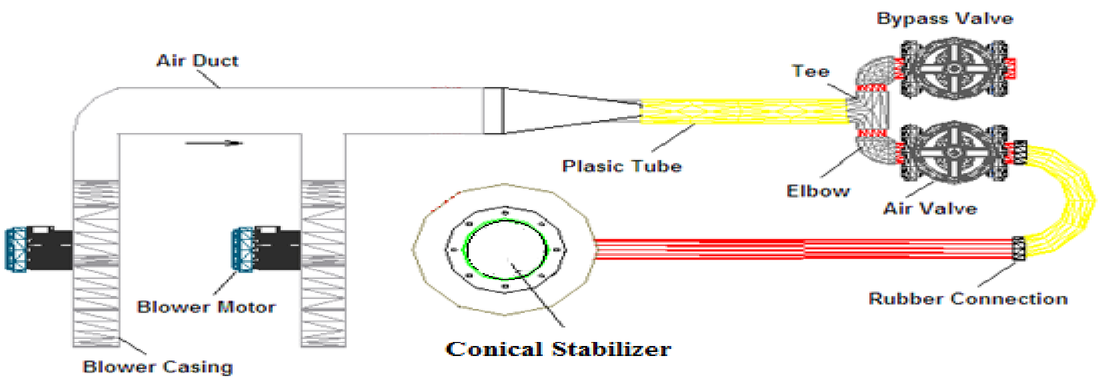


Figure (1): Plan View for Test rig System Main Parts

The conical stabilizer

The design of conical stabilizer used shown in figure (1) is designed such as the gas flows through nozzles which were drilled in co-axial cylindrical recesses. These recesses were created using internal turning for an externally tapered disc of 186 mm diameter and thickness of 62 mm.

The recesses diameters ranging from 22 mm up to 150 mm with step 32 mm and height of 8 mm. the jets were frilled around the recesses circumference. The holes were drilled such as that they are inclined by an angle 38 ^{o} to line that drown from the circle center to the hole center in the vertical plane as shown in figure (2) and 10 ^{o} in the horizontal plane as shown in figure (3) the last angle is selected to create swirl in the flow and the other design is the same but with 0 ^{o} in the horizontal plane

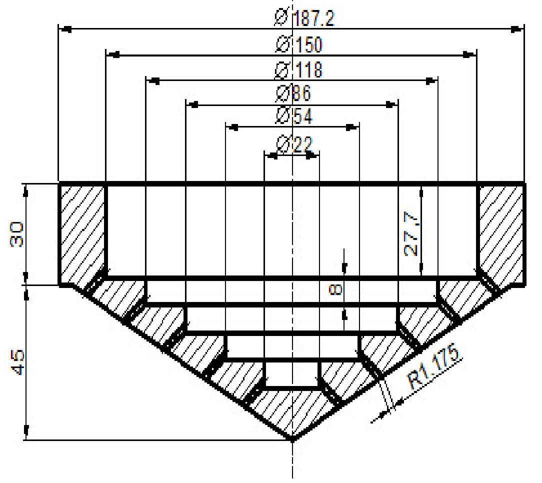


Figure (2) conical stabilizer

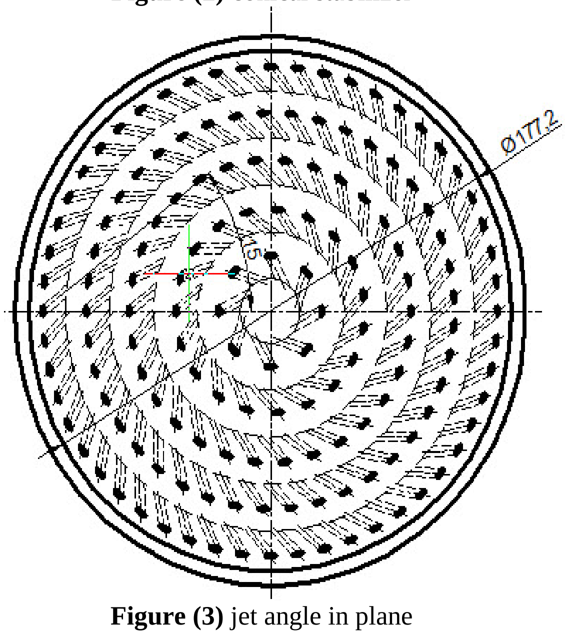


Figure (3) jet angle in plane

Air supply and control system

A controlled quantity of air is supplied to the test section by two centrifugal blowers (5.5 hp, 2880 rpm) through a pipe line which is branched into two lines; one of them is directed to the measuring device and then to test section and the other is connected to bypass valve as shown in Fig. 1. The two branches are integrated with manual gate valves to achieve the desired volume flow rate. The air mass flow rate is measured by measuring air velocity, V_a, through a Pitot tube, which is placed at distance of 2000mm from the control valve. The Pitot tube readings are measured by a multi tube manometer that determines the total and static pressures. The airflow line is provided with a layer of wire mesh located at the exit of the control valve, to ensure homogeneity of flow. The air mass flow rates, $\dot{m}_a$, are calculated as:

$$\dot{m}_a = \rho_a V_a A$$

Where:

$$V_a = \sqrt{2\,g\,h_a}$$

Fuel supply and control system

Natural gas is used here and preferred for its low wastes and the high flammability limits. A natural gas fuel was injected into the air stream at sufficient distance before the conical stabilizer to provide uniform homogeneous gas mixture flowing into the burner. The use of a gaseous fuel avoids the problem of pre-vaporization (especially for operation at room temperature). The amount of fuel is determined and controlled by using a fuel volume flow meter which is provided with a control valve to adjust the fuel flow rate. The fuel flow meter is connected to the fuel injection point through a flexible gas tube. The fuel mass flow rates, $\dot{m}_f$, are calculated as:

$$\dot{m}_f = \rho_f \dot{Q}_f$$

Where:

$\dot{Q}_f$ Fuel volume flow rate

Table (1) shows the properties of the natural gas used in the present study.
Data sheet from Cairo gas company (PETROGAS)

Calorific value	42852 kJ/kg
Density	0.754 kg/m^3
Correct (A/F)	17.2
Molecular weight	18.87

Experimental test procedures:

The air mass flow rate is adjusted and recorded. The fuel mass flow rate is recorded and the mixture is ignited at first by a flame torch until the flame is established behind the conical stabilizer. Then the fuel mass flow rate is gradually decrease and recorded until the blow off occurs. For each recorded fuel mass flow rate a direct photography of the flame is taken. In order to study the effect of the equivalence ratio, and exit jet angle on the blow off, the exit jet for the conical stabilizer have an angles 38 degree on horizontal line and 10 degree on vertical line and the other one 38 degree on horizontal line and zero degree on vertical line.

Experimental Results:

A combustion run test performed with test rig facility for the conical stabilizer with ejectors configuration. The combustion run test performed at two different velocities of air and different amount of fuel for each velocity. The photo illustrated in figure (4), figure (5), figure (6) and figure (7).

For figure (4) the test for conical stabilizer which has an ejector angle of 38 degree on horizontal axis and 10 degree on vertical axis is illustrated. The fuel changed four times and every time takes a photo. It is clear that the ejector with the suggested configuration for the conical stabilizer achieved good swirl in products of combustion. And there is a stability of flame over the conical stabilizer. Another run performed with the same facility for another air velocity the captured shots are illustrated at figure (5). It is clear that the more air velocity increase the more swirl in products gases and the flame length be small. The swirling of flame is around the vertical axis.

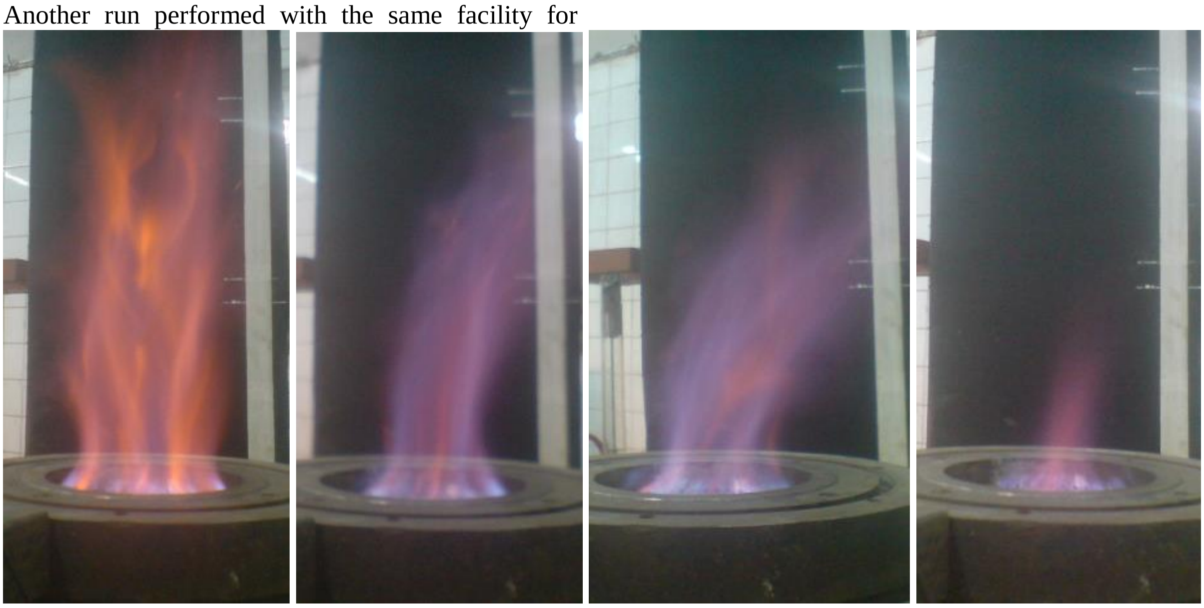
A/F=39.7 A/F=41.7 A/F=43.8 A/F=76.3

Figure(4): combustion run for conical stabilizer with injector have an angle of 38 degree on horizontal axis and 10 degree on vertical axis at v= 4.29 m/s

A/F= 46.9 A/F=51.6
A/F=54.3
A/F=73.7

Figure(5): combustion run for conical stabilizer with injector have an angle of 38 degree on horizontal axis and 10 degree on vertical axis at v=5.06 m/s

For figure (6) the test for conical stabilizer which has an ejector angle of 38 degree on horizontal axis and 0 degree on vertical axis is illustrated. The fuel changed four times and every time takes a photo. It is clear that the ejector with o degree on vertical axis has low swirl than the other conical stabilizer. Another run performed with the same facility for another air velocity the captured shots are illustrated at figure (7). It is clear that when air velocity increases the swirl in products gases appear and the flame length is higher than the other conical stabilizer.



A/F=41.7 A/F=43.7 A/F=46 A/F=67

Figure(6): combustion run for conical stabilizer with injector have an angle of 38 degree on horizontal axis and 0 degree on vertical axis at v= 4.29 m/s

A/F=49.1 A/F=51.6 A/F=54.3 A/F=69.8

Figure(7): combustion run for conical stabilizer with injector have an angle of 38 degree on horizontal axis and 0 degree on vertical axis at v=5.06 m/s

In order to indicate the change in performance of the two design of conical stabilizer on flame stability, the blow off limit for the two geometries are plotted as a relationship between the blow off air - fuel ratio ($A/F_{at\ blow\ off}$) and air velocity as given in Figure (8). It is obvious that as the air velocity increases the blow off air-fuel ratio decreases for the same design. For the same air velocity the highest value of the blow off air-fuel ratio occurs with using conical stabilizer 1 (with 38 degree on horizontal and 10 degree on vertical). The improvement occurred in the case of the cone stabilizer 1 which shows the best behavior compared to the other one. The improvement shown can be attributed to that the conical stabilizer with jet inclined on vertical axis makes the stream lines of the combustible mixture exhibit good swirl, so it leads to increase the weak blow off limit which improve stability of the flame.

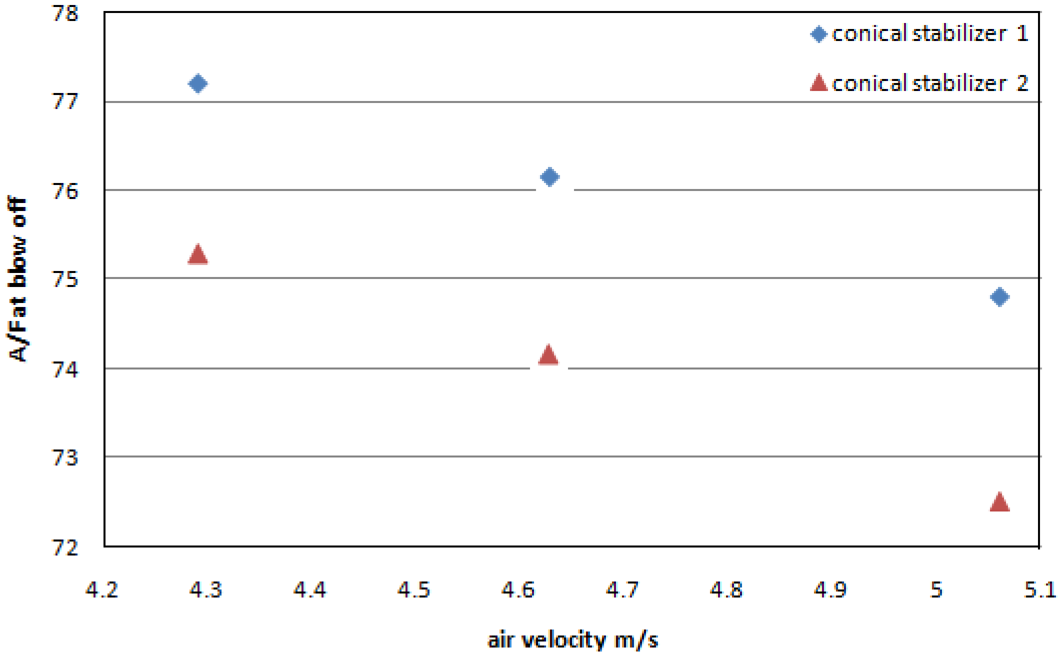


Figure (8) Variation of air-fuel ratio at blow off with air velocity for two design of conical stabilizer

Conclusion:

The main objective of this work is to study the effect of design of conical stabilizer with different inclination angles of jets on the flame stability for a free premixed flame of Natural Gas. For this reason a burner with conical stabilizer is installed. Different inclined jet angles used; conical stabilizer 1 (with jet have an angle of 38 degree on horizontal axis and 10 degree on vertical axis) conical stabilizer 2 (with jet have an angle of 38 degree on horizontal axis and 0 degree on vertical axis). For each conical stabilizer, tests are done at the same velocity of air and different air to fuel ratio and measurements are performed for flame length by photographic technique.

Based on the different experimental runs performed here and the discussion of the results, the following conclusions are obtained:

1) The conical stabilizer has improve the flame stability extend of free flame.
2) There is a noticeable improvement in the stability limits by making the exit jet with angle on vertical axis for higher velocities of the premixed mixture.
3) The conical stabilizer 1 has an effect on the stability limit more than on the conical stabilizer 2.

Nomenclature:

A/F	**measured fuel to air ratio**	
$\dot{m}_a$	**air mass flow rate**	kg/s
V_a	**air average velocity** $V_a = \sqrt{2\ g\ h_a}$	m/s
ρ_a	**air density** $\rho_a = P_a/(RT_a)$	kg/m^3
$\dot{m}_f$	**fuel mass flow rate**	kg/s

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