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ANALYSIS OF ALTITUDE COMPENSATION SYSTEMS FOR AIRCRAFT CARBURETORS

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SUMMARY

An analysis of aircraft-carburetor design with emphasis on air-flow equations, and altitude- or density-compensation systems is presented. Several theoretically perfect methods of compensating carburetors for density are developed and the resulting compensation equations are set up for air density sensed as a single variable and for air density sensed by separate indications of pressure and temperature.

An approximation of the theoretical air-flow equation has been presented for carburetor use that has a maximum deviation of ±1.5 percent from the theoretical equation. It has been found that the simplest means of compensating for the variation in air density is that of varying the area of the venturi as a function of air density; this method also offers the advantage of increased air-flow capacity at altitude. Air-side compensation, or variation of the effective venturi pressure drop, as used in present carburetors was found to be one of the more complicated methods.

INTRODUCTION

The problem of accurate fuel metering for aircraft engines has become of increasing importance in recent years because of the development of long-range, high-altitude aircraft. In the use of service carburetors, difficulties in metering fuel correctly at high altitudes have been encountered mainly because of errors in altitude compensation, or more exactly, density compensation. At high altitudes, the magnitude of these errors may be 30 percent or more. Because the performance of an aircraft engine is affected to a considerable extent by the accuracy of fuel metering, an analysis of the fuel-metering characteristics of the aircraft carburetor with regard to air-flow and fuel-flow measurement and proportioning will be valuable in improving the performance of aircraft engines.

The requirements for the measurement of air flow and fuel flow are discussed herein and an analysis of several methods of density compensation, which was conducted at the NACA Lewis laboratory, is presented.

ANALYSIS OF PROBLEM

The function of a fuel-metering device is to meter fuel to the engine in a definite weight ratio to the engine air flow. This ratio must be maintained between certain limits to provide an inflammable mixture and should be controlled accurately enough to provide metering at the maximum-economy or at the maximum-power fuel-air ratio. The problem is therefore one of correlating the weight flow of fuel to the weight flow of air. Because air flow is the primary variable, it becomes necessary to use the characteristics of the air-flow measuring device to control fuel flow.

Air-Flow Measurement

The air-flow measuring element used in a carburetor should be accurate and reliable, provide a simple measurable indication of air flow, and have a small pressure loss. The venturi has been used in carburetors as an air-flow measuring element because it most nearly fulfills these requirements.

Because the flow of fuel is to be controlled by the indication of air flow obtained from the venturi, the air-flow equation of the venturi must be known. This equation should first of all be theoretically correct. Approximations to it may then be made if such approximations are necessary to simplify the carburetor design. The theoretical equation for air flow through a venturi is developed in appendix A and an approximation of this equation, which has a maximum deviation from the theoretical equation of about ±1.5 percent over the air-flow range, is as follows:

$$W^2 = (0.985)^2 C^2 A_2^2 \frac{2g}{R} \frac{p_2}{T_0} (P_0 - p_2) \tag{1}$$

(All symbols are defined in appendix B.)

Equation (1) indicates that for a constant-area venturi, three variables (p_2, T_0, and $P_0 - p_2$) must be combined to obtain a correct indication of the air flow W.

Fuel-Flow Measurement

The requirements of a fuel-flow measuring element are that it be accurate and reliable, and that it provide a simple measurable indication of fuel flow. Because the pressure loss of the element is usually unimportant, there is considerable latitude of choice in selecting a fuel-flow element. Special fuel-flow elements, called metering jets, have generally been used in carburetors principally because of ease of manufacture, duplication, and calibration. These jets have more or less rounded entrances and a throat section with a large length-to-diameter ratio, and therefore have characteristics very similar to those of a flow nozzle. The equation for flow of a liquid through a flow nozzle, developed in appendix A, is as follows:

$$(W')^2 = (C')^2 \ (A_2')^2 \ 2g \ \rho' \ (p_1' - p_2') \tag{2}$$

Correlation of Air Flow and Fuel Flow

For a constant fuel-air ratio, the characteristics of the air venturi must be correlated with the characteristics of the fuel jet. Equations (1) and (2) may be combined to form the following relation:

$$\frac{W^2}{(W')^2} = \frac{(0.985)^2 \ C^2 \ A_2{}^2 \ \frac{2g}{R} \frac{p_2}{T_0} \ (P_0 - p_2)}{(C')^2 \ (A_2')^2 \ 2g \ \rho' \ (p_1' - p_2')}$$

or

$$K \ A_2{}^2 \ \frac{p_2}{T_0} \ (P_0 - p_2) = (A_2')^2 \ (p_1' - p_2') \tag{3}$$

where

$$K = \frac{(0.985)^2 \ (W')^2 \ C^2}{R \ \rho' \ W^2 \ (C')^2}$$

in which ρ' is assumed constant. The term p_2/T_0 may be considered a fictitious density ρ_x. Equation (3) then becomes

$$K_1 \ A_2{}^2 \ \rho_x \ (P_0 - p_2) = (A_2')^2 \ (p_1' - p_2') \tag{4}$$

where

$$K_1 = KR$$

because

$$\rho_x = \frac{p_2}{RT_0}$$

In equations (3) and (4), the terms p_2, T_0, and $P_0 - p_2$ are independent variables. All other terms (except K or K_1) may be made to depend on these independent variables. Carburetion-design practice has been to equate the air-pressure drop $P_0 - p_2$ to the fuel-pressure drop $p_1' - p_2'$. (In most service carburetors, a compensated value of $P_0 - p_2$ is equated to $p_1' - p_2'$; however, this is a method of compensating for variations in the density ρ_x and will be discussed later in the report.) In the float-type carburetor, the pressure drop $P_0 - p_2$ is equated to the pressure drop $p_1' - p_2'$ by introducing the pressure P_0 to the float chamber and causing the fuel to be discharged into the throat of the air venturi. In the pressure-type carburetor, the pressure drop $P_0 - p_2$ is usually equated to the pressure drop $p_1' - p_2'$ through the use of a set of balanced diaphragms. Any unbalance of the diaphragms is used to operate a valve that controls the fuel flow in such a manner that the diaphragms tend to remain balanced. Because of the inherent advantages of the pressure-type carburetors with regard to reliability during aircraft maneuvers, good atomization of fuel due to the high fuel-nozzle pressures possible, and adaptability to positive metering control, only this type of carburetor is considered in the following analysis of density-compensation systems. Some of the systems that will be discussed may, however, be readily applied to float-type carburetors.

ANALYSIS OF SEVERAL DENSITY-COMPENSATION SYSTEMS

Methods of Density Compensation

Several methods of density compensation for a pressure-type carburetor will be considered and are listed as follows:

(1) The pressure difference $P_0 - p_2$ may be equated in a constant ratio to the pressure difference $p_1' - p_2'$, with the area A_2' held constant and the area A_2 made a function of the density ρ_x.

(2) The pressure difference $P_0 - p_2$ may be equated in a constant ratio to the pressure difference $p_1' - p_2'$ with the area A_2 held constant and the area A_2' made a function of the density ρ_x.

(3) The areas A_2 and A_2' may be held constant, the pressure difference $p_1' - p_2'$ combined with the density ρ_x, and the resulting compensated pressure difference equated in a constant ratio to the pressure difference $P_0 - p_2$.

(4) The areas A_2 and A_2' may be held constant, the pressure difference $P_0 - p_2$ combined with the density ρ_x, and the resulting compensated pressure difference equated in a constant ratio to the pressure difference $p_1' - p_2'$.

(5) Any of the variables $P_0 - p_2$, $p_1' - p_2'$, A_2', or A_2, or their effective values, may be made functions of the pressure p_2 or the temperature T_0, as long as $P_0 - p_2$ and $p_1' - p_2'$ or their compensated values are equated in a constant ratio.

In each of the foregoing methods except method (5), it is assumed that a device is available that will give an accurate indication of air density.

Variable-Area Venturi Method

A simple schematic diagram of a carburetor employing a variable-area-venturi compensation system is presented in figure 1. For this system, $P_0 - p_2$ is equated to $p_1' - p_2'$ by use of the air-diaphragm assembly. Equation (4) then becomes

$$K_1 A_2^2 \rho_x = (A_2')^2$$

Solving for A_2 results in

$$A_2 = A_2' \sqrt{\frac{1}{K_1 \rho_x}} \tag{5}$$

which expresses the required relation of A_2 and ρ_x for perfect compensation.

Compensation by this method also has an advantage in that as ρ_x becomes smaller, the area A_2 becomes larger, which means that at altitude the air-flow capacity of the variable-area-venturi carburetor is greater than that of the fixed-area-venturi carburetor when the two have equal venturi areas at sea level.

Variable-Area Fuel-Jet Method

A simple schematic diagram of a carburetor employing a variable-area fuel-jet compensation system is shown in figure 2. The air-pressure difference $P_0 - p_2$ is equated to $p_1' - p_2'$ by the diaphragm assembly, and equation (4) then becomes

$$K_1 A_2^2 \rho_x = (A_2')^2$$

Solving for A_2' results in

$$A_2' = A_2 \sqrt{K_1 \rho_x} \tag{6}$$

which expresses the required relation of A_2' and ρ_x for perfect compensation. This system would probably be difficult to manufacture because of the necessarily small area of the fuel jet.

Compensation by Variation of Effective

Fuel-Jet Pressure Drop

In a system that compensates for density by variation of the effective fuel-jet pressure drop, the areas A_2 and A_2' are constant and the effective or compensated fuel-jet pressure differential is equated to $P_0 - p_2$. From equation (4), the compensated fuel-pressure differential must equal a constant times the ratio of the uncompensated fuel-pressure differential $p_1' - p_2'$ and the density ρ_x for perfect compensation. In mathematical form this relation is expressed as

$$(p_1' - p_2')_c = \frac{p_1' - p_2'}{K_2 \rho_x} \tag{7}$$

where the subscript c designates the compensated value and

$$K_2 = \frac{A_2^2 K_1}{(A_2')^2}$$

Four methods of compensation of the fuel-pressure differential are shown in figure 3. The analysis is based on the following assumptions:

(1) The flow through the compensation system is negligible.

(2) The inlet area of the variable restriction is large compared with the throat area; therefore the variation of the velocity of approach factor is negligible for normal variations of the area of the variable restriction.

(3) The coefficients of discharge of the fixed and variable restrictions are virtually constant over the flow range.

(4) The shape of the fixed and variable restrictions is such that their characteristics are similar to a flow nozzle (except in the case where the fixed restriction is a venturi).

(5) The fuel density through the compensation system is constant.

The system shown in figure 3(a) consists of a fixed and variable restriction with the compensated fuel-pressure differential obtained from the pressure drop across the fixed restriction. The notation is as indicated, where $(p_1' - p_2')_c$ equals $P_0 - p_2$. The flow through the compensation system may be expressed by an adaptation of equation (2).

$$
\begin{aligned}
(W_1')^2 &= 2g\ (C_f')^2\ (A_f')^2\ \rho'\ (P_0 - p_2) \\
&= 2g\ (C_v')^2\ (A_v')^2\ \rho'\ (p_v' - p_2')
\end{aligned}
$$

Solving this equation for $(A_v')^2$ results in the following expression:

$$
(A_v')^2 = \frac{(C_f')^2\ (A_f')^2\ (P_0 - p_2)}{(C_v')^2\ (p_v' - p_2')} \tag{8}
$$

The required relation of the various pressures to density ρ_x for perfect compensation is given by equation (7), which is rewritten in the notation of figure 3(a) as follows:

$$K_2 \rho_x = \frac{p_1' - p_2'}{P_0 - p_2} \tag{9}$$

In order to determine the required variation of the area A_v' with density, it is first necessary to express equation (8) in terms of $\frac{p_1' - p_2'}{P_0 - p_2}$. It will be noted from figure 3(a) that

$$p_v' - p_2' = (p_1' - p_2') - (P_0 - p_2)$$

Substitution of this expression for $p_v' - p_2'$ in equation (8) results in

$$(A_v')^2 = \frac{(C_f')^2 \ (A_f')^2 \ (P_0 - p_2)}{(C_v')^2 \ \left[(p_1' - p_2') - (P_0 - p_2)\right]}$$

Simplifying yields

$$(A_v')^2 = \frac{(C_f')^2 \ (A_f')^2}{(C_v')^2 \left(\dfrac{p_1' - p_2'}{P_0 - p_2} - 1\right)}$$

Combining this expression with the equation expressing the relation that must hold for perfect compensation (equation (9)) results in

$$(A_v')^2 = \frac{(C_f')^2 \ (A_f')^2}{(C_v')^2 \ (K_2 \rho_x - 1)}$$

or

$$A_v' = K_3' \sqrt{\frac{1}{(K_2 \rho_x - 1)}} \tag{10}$$

where

$$K_3' = \frac{C_f' \ A_f'}{C_v'}$$

This system will compensate perfectly if the area of the variable restriction A_v' is varied with density ρ_x as expressed by equation (10).

Figure 3(b) represents a system similar to the one just described, except that the positions of the fixed and variable restrictions are reversed. It can be shown by a method similar to the preceding method that the required variation of A_v' with density ρ_x is the same as equation (10).

A third method for compensation by variation of the fuel-jet pressure drop is shown in figure 3(c). In this method the jet-type fixed restriction of figure 3(a) has been replaced by a venturi so that pressure recovery is obtained. The following analysis is based on the assumption that complete pressure recovery is obtained so that the pressure downstream of the venturi equals the pressure upstream. With the notation shown, the equation for flow through the compensation system is

$$\begin{aligned}(W_1')^2 &= 2g\ (C_f')^2\ (A_f')^2\ \rho'\ (P_0 - p_2) \\ &= 2g\ (C_v')^2\ (A_v')^2\ \rho'\ (p_1' - p_2')\end{aligned}$$

Solving for $(A_v')^2$ yields

$$(A_v')^2 = \frac{(C_f')^2\ (A_f')^2\ (P_0 - p_2)}{(C_v')^2\ (p_1' - p_2')}$$

The equation for perfect compensation (equation (7)) with the notation of figure 3(c) is

$$P_0 - p_2 = \frac{p_1' - p_2'}{K_2\ \rho_x}$$

or

$$\frac{P_0 - p_2}{p_1' - p_2'} = \frac{1}{K_2\ \rho_x}$$

Combining these two equations results in

$$(A_v')^2 = \frac{(C_f')^2\ (A_f')^2}{(C_v')^2\ K_2\ \rho_x}$$

or

$$A_v' = K_3' \sqrt{\frac{1}{K_2\ \rho_x}} \tag{11}$$

An alternative method is shown in figure 3(d). It can be shown by the same process that the required variation of A_v' with density ρ_x is the same as equation (11).

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Compensation by Variation of Effective Value of Venturi Pressure Drop

In a system that compensates for density by varying the effective value of the venturi pressure drop $P_0 - p_2$, the areas A_2 and A_2' are constant and the effective or compensated value of $P_0 - p_2$ is equated to $p_1' - p_2'$. For perfect compensation with this system, the compensated value of $P_0 - p_2$ must be equal to a constant times the product of the uncompensated value of $P_0 - p_2$ and the density ρ_x. In mathematical form this relation is expressed as

$$(P_0 - p_2)_c = K_2 \, \rho_x \, (P_0 - p_2) \tag{12}$$

Four methods of varying the effective value of the venturi pressure drop $P_0 - p_2$ are shown in figure 4. The analysis is based on the following assumptions:

(1) The mass flow through the compensation system is negligible.

(2) The inlet area of the variable restriction is large compared with the throat area; therefore the variation of the velocity of approach factor is negligible for normal variations of the area of the variable restriction.

(3) The coefficients of discharge of the fixed and variable restrictions are virtually constant over the flow range.

(4) The shape of the fixed and variable restrictions is such that their characteristics are similar to a flow nozzle (except in the case where the fixed restriction is a venturi).

(5) The stagnation temperature is the same throughout the compensation system.

Figure 4(a) shows the system used in some of the pressure-type carburetors, which consists of a fixed and variable restriction in series. The pressure differential $P_0 - p_2$ is imposed across the restrictions in series and the compensated pressure difference is obtained from the pressure drop across the fixed restriction. The notation is as indicated, where $P_0 - p_v$ is equal to $(P_0 - p_2)_c$. The flow through the compensation system may be expressed by an adaptation of equation (1).

$$W_1^2 = \frac{(0.985)^2\ 2g}{R} C_f^2 A_f^2 \frac{p_v}{T_0} (P_0 - p_v)$$

$$= \frac{(0.985)^2\ 2g}{R} C_v^2 A_v^2 \frac{p_2}{T_0} (p_v - p_2)$$

Solving this equation for A_v^2 results in the following expression:

$$A_v^2 = \frac{C_f^2 A_f^2 p_v (P_0 - p_v)}{C_v^2 p_2 (p_v - p_2)} \tag{13}$$

The required relation of the various pressures to density ρ_x for perfect compensation is given by equation (12), which is rewritten in the notation of figure 4(a) as follows:

$$K_2 \rho_x = \frac{P_0 - p_v}{P_0 - p_2} \tag{14}$$

In order to determine the required relation of A_v to ρ_x or other variables that may be involved, it is necessary to express the $(P_0 - p_v)/(p_v - p_2)$ term of equation (13) in terms of $(P_0 - p_v)/(P_0 - p_2)$. It will be noted from an examination of figure 4(a) that

$$p_v - p_2 = (P_0 - p_2) - (P_0 - p_v)$$

Substitution of this expression for $p_v - p_2$ in equation (13) results in

$$A_v^2 = \frac{C_f^2 A_f^2 p_v (P_0 - p_v)}{C_v^2 p_2 \left[(P_0 - p_2) - (P_0 - p_v)\right]}$$

or

$$A_v^2 = \frac{C_f^2 A_f^2 p_v}{C_v^2 p_2 \left(\dfrac{P_0 - p_2}{P_0 - p_v} - 1\right)} \tag{15}$$

Because equation (14) expresses the required relation of $(P_0 - p_v)/(P_0 - p_2)$ to density ρ_x for perfect compensation, equations (14) and (15) may be combined (subject to aforementioned assumption (1)) to find the area function for perfect compensation. Simplifying yields

$$A_v^2 = \frac{c_f^2 \; A_f^2 \; p_v \; K_2 \; \rho_x}{c_v^2 \; p_2 \; (1 - K_2 \; \rho_x)}$$

or

$$A_v = K_3 \sqrt{\frac{p_v \; K_2 \; \rho_x}{p_2 \; (1 - K_2 \; \rho_x)}} \tag{16}$$

where

$$K_3 = \frac{c_f \; A_f}{c_v}$$

For proper compensation, this system requires that the area of the variable orifice be varied as a function of the density and the pressure ratio p_v/p_2. In the conventional carburetor that uses the system shown in figure 4(a), this pressure ratio is neglected with the result that a variation of fuel-air ratio is caused. The magnitude of this variation is approximately proportional to the square root of the variation of the pressure ratio.

Figure 4(b) is a diagram of a compensation system similar to that used in some other pressure-type carburetors. It is the same as the system previously analyzed except that the positions of the fixed and variable restrictions are reversed. The notation is as shown in figure 3(b). From equation (12) the equation for perfect compensation is

$$p_v - p_2 = K_2 \; \rho_x \; (P_0 - p_2)$$

and from equation (1) the equation for flow through the compensation system is

$$\frac{(0.985)^2 \; 2g}{R} \, c_v^2 \; A_v^2 \; \frac{p_v}{T_0} \, (P_0 - p_v) = \frac{(0.985)^2 \; 2g}{R} \, c_f^2 \; A_f^2 \; \frac{p_2}{T_0} \, (p_v - p_2)$$

It can be shown by a process similar to the method previously used that the required area function for perfect compensation is

$$A_v = K_3 \sqrt{\frac{p_2 \; K_2 \; \rho_x}{p_v \; (1 - K_2 \; \rho_x)}} \tag{17}$$

which is the same as equation (16) except that the pressure ratio p_v/p_2 is inverted. In the conventional carburetor that uses this system, this pressure ratio is also neglected, which causes errors similar to those noted for the previous system.

A third type of system in use on some carburetors is diagrammatically shown in figure 4(c). A venturi is used as a fixed restriction instead of a type of restriction approximating a flow nozzle as in the two foregoing systems. The following analysis is based on the assumption that there is complete pressure recovery so that the pressure downstream of the fixed restriction is the same as the pressure upstream. The notation is as indicated in figure 4(c). The equation for perfect compensation is

$$P_0 - p_v = K_2 \; \rho_x \; (P_0 - p_2)$$

or

$$\frac{P_0 - p_v}{P_0 - p_2} = K_2 \; \rho_x \tag{18}$$

and the equation for flow through the compensation system is

$$\frac{(0.985)^2 \; 2g}{R} \; C_f^2 \; A_f^2 \; \frac{p_v}{T_0} \; (P_0 - p_v) = \frac{(0.985)^2 \; 2g}{R} \; C_v^2 \; A_v^2 \; \frac{p_2}{T_0} \; (P_0 - p_2)$$

or

$$A_v^2 = \frac{C_f^2 \; A_f^2 \; p_v \; (P_0 - p_v)}{C_v^2 \; p_2 \; (P_0 - p_2)} \tag{19}$$

Equations (18) and (19) may be combined to find the area function for perfect compensation as follows:

$$A_v^2 = \frac{C_f^2 \; A_f^2}{C_v^2} \; \frac{p_v}{p_2} \; K_2 \; \rho_x$$

In the development of equation (4) it will be noted that

$$\rho_x = \frac{p_2}{RT_0}$$

The preceding equation then becomes

$$A_v^2 = \frac{C_f^2 A_f^2}{C_v^2} \frac{p_v K_2}{RT_0}$$

When the quantity p_v/RT_0 is defined as a fictitious density ρ_y, the preceding equation becomes

$$A_v^2 = \frac{C_f^2 A_f^2}{C_v^2} K_2 \rho_y$$

or

$$A_v = K_3 \sqrt{K_2 \rho_y} \tag{20}$$

Comparison of equation (20) with equations (16) or (17) indicates that compensation by this method is much easier because the required area of the variable restriction A_v is a function of only the density. In the conventional carburetor, which employs this system, the density bellows is not bled to the density ρ_y but to the density ρ_2, which causes some error at high altitude due to the change in proportionment of air flow between the main venturi and the compensating-system venturi.

A variation of the foregoing system is shown in figure 4(d), which is the same as figure 4(c) except that the positions of the fixed and variable restrictions are reversed. Again the assumption is made that the pressure recovery of the venturi is complete (that is, the pressure upstream of the venturi equals the pressure downstream). The notation is as indicated on figure 4(d). The equation for perfect compensation is

$$p_2 - p_v = K_2 \rho_x (P_0 - p_2)$$

and the equation for flow through the compensation system is

$$\frac{(0.985)^2 2g}{R} C_f^2 A_f^2 \frac{p_v}{T_0} (p_2 - p_v) = \frac{(0.985)^2 2g}{R} C_v^2 A_v^2 \frac{p_2}{T_0} (P_0 - p_2)$$

It can be shown by a process similar to the one used in the foregoing discussion that the required area function for perfect compensation is

$$A_v = K_3 \sqrt{K_2 \rho_y} \tag{21}$$

where again ρ_y is a fictitious density composed of the pressure at the throat of the compensating venturi and the stagnation temperature of the system.

Compensation by Means of Pressure p_2 and Temperature T_0

The foregoing methods of compensation require the use of a device that will give an indication of air density. Reference 1 shows that the conventional pressure-temperature-sensitive bellows will not give an acceptably accurate indication of air density except over a very narrow density range. Therefore, methods of compensation will be investigated where compensation for variations in pressure and temperature are made by separate elements. It will be noted from an examination of equation (3) that the following additional methods of compensation are possible. In all cases, the values of $P_0 - p_2$ and $p_1' - p_2'$ or their compensated values are equated in a constant ratio and all other variables except those being varied by pressure or temperature are considered constant. The compensated values of $P_0 - p_2$ and $p_1' - p_2'$ are indicated by the subscript c.

1. $(P_\Theta - p_2)_c = f(p_2)$ and $(p_1' - p_2')_c = f(T_0)$

or

$$(p_1' - p_2')_c = f(p_2) \quad \text{and} \quad (P_0 - p_2)_c = f(T_0)$$

2. $A_2^2 = f(p_2)$ and $(A_2')^2 = f(T_0)$

or

$$(A_2')^2 = f(p_2) \quad \text{and} \quad A_2^2 = f(T_0)$$

3. $(P_0 - p_2)_c = f(p_2)$ and $A_2{}^2 = f(T_0)$

or

$$A_2{}^2 = f(p_2) \quad \text{and} \quad (P_0 - p_2)_c = f(T_0)$$

4. $(p_1' - p_2')_c = f(p_2)$ and $A_2{}^2 = f(T_0)$

or

$$A_2{}^2 = f(p_2) \quad \text{and} \quad (p_1' - p_2')_c = f(T_0)$$

5. $(P_0 - p_2)_c = f(p_2)$ and $(A_2')^2 = f(T_0)$

or

$$(A_2')^2 = f(p_2) \quad \text{and} \quad (P_0 - p_2)_c = f(T_0)$$

6. $(p_1' - p_2')_c = f(p_2)$ and $(A_2')^2 = f(T_0)$

or

$$(A_2')^2 = f(p_2) \quad \text{and} \quad (p_1' - p_2')_c = f(T_0)$$

The required relations of the dependent variables, $(p_1' - p_2')_c$, $(P_0 - p_2)_c$, A_2', and A_2, to the independent variables p_2 and T_0 may be found by the same methods employed for the foregoing methods of compensation. (Equation (3) is used instead of equation (4) as the equation for the weight-flow correlation.)

As an example, for combination (1), the compensation equations are obtained as follows:

Equation (3) is the equation for perfect compensation and is rewritten as follows:

$$K_4 \, A_2{}^2 \, p_2 \, (P_0 - p_2) \doteq (A_2')^2 \, \frac{T_0}{K_5} \, (p_1' - p_2')$$

where

$$K_4 K_5 = K$$

As usual, it is desirable to let the compensated values of $(P_0 - p_2)$ and $(p_1' - p_2')$ equal each other. Thus the following equations may be written

$$(P_0 - p_2)_c = (p_1' - p_2')_c$$

$$(P_0 - p_2)_c = K_4 A_2^2 p_2 (P_0 - p_2) \tag{22}$$

$$(p_1' - p_2')_c = (A_2')^2 \frac{T_0}{K_5} (p_1' - p_2') \tag{23}$$

Equations (22) and (23) are the relations that must be maintained to achieve perfect compensation for the method chosen. Any of the methods shown in figure (4) may be used to achieve equation (22) and any of the methods shown in figure (3) may be used to achieve equation (23). The mathematical methods used to obtain the required variation of the variable area are the same as described for these methods with the exception that equation (22) in the one case and equation (23) in the other case are the equations for perfect compensation instead of equation (7).

It is not considered necessary to show the development of each of these required relations because of the similarity to the methods employed in analyzing the foregoing systems for compensation. The required relations, however, for all the possibilities listed in items 1 to 6 are shown in table I. The required relations for compensation of the dependent variables for density are also shown.

Table I is set up in the following manner: The dependent variables as functions of pressure p_2 are listed to the left of the rows and the dependent variables as functions of temperature T_0 are listed at the heads of the columns. If it is desired to vary one dependent variable as a function of pressure and another as a function of temperature, the equations for the required relations are found at the intersection of the respective rows and columns. It is necessary to select one equation for variation with pressure and one for variation with temperature. In cases where the dependent variables are $(p_1' - p_2')_c$ or $(P_0 - p_2)_c$, the equations are given for the required variation of A_v or A_v' for each of the cases listed in figures 3 and 4, respectively. If it is desired to vary a dependent variable as a function of density, the required relations are again found at the intersection of the respective row and column. For this case, the equations for the required relations are given in terms of density.

DESIGN CONSIDERATIONS

Air- and Fuel-Flow Measuring Elements

The accuracy of indication of flow rate obtained from the air- and fuel-flow measuring elements will depend to a considerable extent on the installation characteristics. In the development of the air-flow equations, the inlet total pressure was the average of the total pressures over the inlet area. In the actual installation, relatively few total-pressure tubes can be tolerated. The installation should therefore be such as to insure a flat velocity profile upstream of the flow-measuring elements. In the case of the fuel-flow element, the inlet chamber should be large (with a diameter ratio - inlet to throat - greater than about 7:1 to 10:1), thus providing good entrance streamlines.

The actual design of the air- and fuel-flow measuring elements should, of course, follow the designs recommended for standard venturis and flow nozzles.

Compensation Systems

Variable-area venturi. - Aside from mechanical-design difficulties, the variable-area-venturi method of compensation is probably the best method of compensating for changes in air density because of its greater air-flow capacity at altitude as compared with a fixed-area venturi. The required variation of venturi area with density is very simple and could be accomplished with a servosystem operating from the fuel-inlet pressure to provide the power amplification from the density-sensing device.

Variable-area fuel jet. - The variable-area fuel-jet method of compensating for changes in air density is probably the second-best method of compensation because of its simplicity and inherent accuracy. Again, however, the mechanical design is difficult because of the small areas required for the fuel jet. This problem is less pronounced with the larger carburetors. As with the variable-area venturi, the required variation of the area of the fuel jet is a simple function of air density and could be accomplished with a servosystem operating from the fuel-inlet pressure to provide the power amplification of the indication of density obtained from the density-sensing device.

Variation of effective fuel-jet pressure drop. - The four methods of compensation by variation of fuel-jet pressure drop are simple and easily applied. Certain assumptions in the development of the compensation equations have, however, been made. These assumptions are:

(1) The flow through the compensation system is negligible.

(2) The inlet area of the variable restriction is large compared with the throat area; therefore the variation of the velocity of approach factor is negligible for normal variations of the area of the variable restriction.

(3) The coefficients of discharge of the fixed and variable restrictions are virtually constant over the flow range.

(4) The shape of the fixed and variable restrictions is such that the characteristics are similar to a flow nozzle (except in the case where the fixed restriction is a venturi).

(5) The fuel density through the compensation system is constant.

Obviously, the error in fuel-air ratio caused by the flow through the compensation system can never be made zero, but it can be reduced to a negligible amount by making the area of the fixed restriction small in comparison with the fuel jet. The maximum error caused by this factor will be approximately the ratio of fixed-restriction area to the fuel-jet area. The second assumption was made so that the variation of the velocity of approach factor with variation of the area of the variable restriction would be small. If total pressures may be used so that the velocity of approach factor is zero, then this assumption need not be considered in the design of the compensation system. The third assumption is one that can be fulfilled by designing the system insofar as possible to operate at high values of Reynolds number. The fourth assumption can be fulfilled by using fixed and variable restrictions with rounded or tapered entrances and high ratios of throat length to diameter. The standard jets now being used in carburetors fulfill these requirements for the fixed restrictions. For the variable restriction, the necessary tapered valves should give characteristics similar to a flow nozzle. In the cases where venturis are used, this assumption, of course, does not apply. The validity of assumption (5) depends on the fuel temperature, which in most installations will be virtually constant.

Variation of effective venturi pressure drop. - Two of the methods of compensation by variation of the venturi pressure drop are rather complicated in that a pressure ratio must be sensed in addition to air density. The two methods employing the small venturis are much simpler and are therefore preferable.

The first four assumptions made for compensation by variation of the fuel-jet pressure drop were also made for compensation with this system and the same design considerations apply. One additional assumption was made in connection with this type of compensation system: The stagnation temperature throughout the compensation system is the same. This assumption will hold true if there is no heat loss nor gain in the compensation system.

When this type of compensation system is employed, the area of the impact tubes at the entrance to the main venturi should be large so that the velocity through the impact tubes is nearly zero.

Use of separate pressure and temperature compensation. - Table I presents the compensation equations to be used when separate compensations are made for pressure and temperature. In general, this type of compensation introduces added complexity and may be too complicated for practical application except when applied to the variable-area venturi or variable-area fuel-jet methods.

In view of the shortcomings of pressure-temperature-sensitive bellows (reference 1), it appears that it would be better to use separate pressure- and temperature-responsive elements, to obtain their ratio by a suitable dividing mechanism, and to apply this indication of density according to one of the equations requiring an indication of density.

When any combination of the foregoing compensation systems is used to make separate compensation for pressure and temperature, the systems should embody the same design features as previously outlined.

SUMMARY OF ANALYSIS

An analysis of aircraft-carburetor design with emphasis on air-flow equations and density-compensation systems is presented. Several theoretically perfect methods of compensating carburetors for density are developed. The results of the analysis may be summarized as follows:

1. A prerequisite to any carburetor design is the use of an accurate air-flow equation for the air-measuring element. An approximation of the theoretical air-flow equation for a venturi is presented, which has a maximum deviation from the theoretical of approximately ±1.5 percent.

2. Aside from mechanical-design difficulties, compensation by variation of the venturi area appeared to be the best of the methods considered because of its simplicity and the fact that the maximum air-flow capacity would be increased at altitude. Compensation by variation of the fuel-jet area or by variation of the effective fuel-jet differential was also good. Compensation on the air side (variation of the effective venturi pressure drop), in general, proved to be complicated although the use of a venturi in the air-side compensation system was no more complicated than the fuel-side compensation systems. Separate compensation for pressure and temperature was, in general, considered too complicated except when applied to the variable-area-venturi or variable-area fuel-jet methods.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 18, 1949.

APPENDIX A

DEVELOPMENT OF FLOW EQUATIONS FOR FLOW OF COMPRESSIBLE AND INCOMPRESSIBLE FLUIDS THROUGH VENTURIS AND FLOW NOZZLES

Compressible Flow

In the usual equations for compressible flow through venturis and flow nozzles, correction factors are applied to the hydraulic equations and, in general, these equations are not suited for application to automatic measurement and integration because of the complexity of the correction factors. In this development, an attempt will be made to obtain a form of the compressible-flow equation that is simple, as regards the number of variables and the required integration, and yet is accurate. The variables capable of simple primary automatic measurement are: the total pressure at any area, the static pressure at any area, any pressure difference, and the stagnation (total) temperature at any area. An equation involving any other variables (such as static or free-stream temperature) could not be used for automatic control applications without inherent inaccuracies.

Bernoulli's theorem for compressible fluids is

$$\frac{\gamma}{\gamma - 1} \frac{P_0}{\rho_0} = \frac{\gamma}{\gamma - 1} \frac{p_1}{\rho_1} + \frac{V_1^2}{2g} = \frac{\gamma}{\gamma - 1} \frac{p_2}{\rho_2} + \frac{V_2^2}{2g} \tag{A1}$$

(All symbols are defined in appendix B.) The general equation for flow is

$$W = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 \tag{A2}$$

When the variables that are capable of automatic measurement are considered, it appears that the equation should be developed using the conditions at a stagnation point and at the minimum area. Solving equation (A1) for V_2^2 in terms of P_0/ρ_0 and p_2/ρ_2 and combining with equation (A2) results in

$$W^2 = A_2^2 \rho_2^2 \frac{2g\gamma}{\gamma - 1}\left(\frac{P_0}{\rho_0} - \frac{p_2}{\rho_2}\right)$$

This expression may be put in the general form of the flow equation by multiplying the numerator and the denominator of the right-hand side by $P_0 - p_2$ and rearranging as follows:

$$W^2 = 2g\, A_2^{\,2}\, \rho_2\, (P_0 - p_2)\, \frac{\gamma \rho_2}{(\gamma - 1)\,(P_0 - p_2)} \left(\frac{P_0}{\rho_0} - \frac{p_2}{\rho_2}\right) \qquad \text{(A3)}$$

The adiabatic relation for pressure and density is

$$\frac{P_0}{\rho_0^{\,\gamma}} = \frac{p_2}{\rho_2^{\,\gamma}} = \text{constant}$$

Then

$$\rho_0 = \left(\frac{P_0}{p_2}\right)^{\frac{1}{\gamma}} \rho_2$$

Substituting this expression in equation (A3) gives

$$W^2 = 2g\, A_2^{\,2}\, \rho_2\, (P_0 - p_2) \left[\frac{\dfrac{P_0}{\rho_2 \left(\dfrac{P_0}{p_2}\right)^{\frac{1}{\gamma}}} - \dfrac{p_2}{\rho_2}}{\left(\dfrac{\gamma - 1}{\gamma}\right)(P_0 - p_2)}\right]$$

Dividing the numerator and the denominator of the bracketed term by p_2 results in

$$W^2 = 2g\, A_2^{\,2}\, \rho_2\, (P_0 - p_2) \left[\frac{\left(\dfrac{P_0}{p_2}\right)\left(\dfrac{P_0}{p_2}\right)^{-\frac{1}{\gamma}} - 1}{\dfrac{\gamma - 1}{\gamma}\left(\dfrac{P_0}{p_2} - 1\right)}\right]$$

or

$$W^2 = 2g\, A_2{}^2\, \rho_2\, (P_0 - p_2) \left[\frac{\left(\frac{P_0}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\gamma - 1}{\gamma}\left(\frac{P_0}{p_2} - 1\right)} \right] \tag{A4}$$

But $\rho_2 = p_2/RT_2$ and T_2 cannot be measured by simple automatic means. If the substitution for ρ_2 is made and equation (A4) is multiplied by T_0/T_0, there is obtained

$$W^2 = 2g\, A_2{}^2\, \frac{p_2}{RT_0}\, (P_0 - p_2) \left[\frac{\left(\frac{P_0}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\gamma - 1}{\gamma}\left(\frac{P_0}{p_2} - 1\right)} \right] \frac{T_0}{T_2} \tag{A5}$$

The adiabatic relation between temperature and pressure is

$$\frac{T_0}{T_2} = \left(\frac{P_0}{p_2}\right)^{\frac{\gamma-1}{\gamma}}$$

Equation (A5) then becomes, with the preceding expression in the denominator,

$$W^2 = 2g\, A_2{}^2\, \frac{p_2}{RT_0}\, (P_0 - p_2) \left[\frac{\left(\frac{P_0}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\gamma - 1}{\gamma}\left(\frac{P_0}{p_2}\right)^{\frac{1-\gamma}{\gamma}}\left(\frac{P_0}{p_2} - 1\right)} \right] \tag{A6}$$

or

$$W = \alpha\, A_2 \sqrt{\frac{2g\, p_2}{RT_0}\, (P_0 - p_2)} \tag{A7}$$

where

$$\alpha = \left[\frac{\left(\frac{P_0}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\gamma - 1}{\gamma}\left(\frac{P_0}{p_2}\right)^{\frac{1-\gamma}{\gamma}}\left(\frac{P_0}{p_2} - 1\right)}\right]^{\frac{1}{2}}$$

The flow equation is now in a conventional form involving the variables capable of automatic measurement. Before it can be stated that equation (A7) is a good form of the flow equation for automatic flow measurement, the range of values of the expansion factor α must be determined. A plot of α with pressure ratio P_0/p_2 for air is shown in figure 5. For air the maximum error incurred by neglecting α is approximately 3 percent at the critical pressure ratio or ±1.5 percent if an average value is assumed.

If the average value of 0.985 is assumed, equation (A7) becomes

$$W = (0.985)\ A_2\sqrt{\frac{2g\ p_2}{RT_0}\ (P_0 - p_2)} \tag{A8}$$

For application to an actual venturi, equation (A8) must be multiplied by the coefficient of discharge; it therefore becomes

$$W = C(0.985)\ A_2\sqrt{\frac{2g\ p_2}{RT_0}\ (P_0 - p_2)} \tag{A9}$$

which is a variation of equation (1) in the text.

Incompressible Flow

Bernoulli's theorem for incompressible fluids is

$$\frac{P_0'}{\rho'} = \frac{p_1'}{\rho'} + \frac{(V_1')^2}{2g} = \frac{p_2'}{\rho'} + \frac{(V_2')^2}{2g} \tag{A10}$$

The equation for fluid flow is

$$W' = \rho' A_1' V_1' = \rho' A_2' V_2' \tag{A11}$$

Solving equation (A10) for $(V_2')^2$ in terms of V_1' and p_1' results in

$$(V_2')^2 = 2g\left(\frac{p_1'}{\rho'} + \frac{(V_1')^2}{2g} - \frac{p_2'}{\rho'}\right) \tag{A12}$$

The velocity V_1' may be obtained in terms of A_2', A_1', and V_2' from equation (A11)

$$V_1' = \frac{A_2'}{A_1'} V_2'$$

After substitution of this expression for V_1' in equation (A12), there is obtained

$$(V_2')^2 = \frac{2g\ (p_1' - p_2')}{\rho' \left[1 - \frac{(A_2')^2}{(A_1')^2}\right]}$$

From equation (A11) the weight flow W', then becomes

$$W' = \rho' A_2' \sqrt{\frac{2g\ (p_1' - p_2')}{\rho' \left[1 - \frac{(A_2')^2}{(A_1')^2}\right]}}$$

or in more conventional form

$$W' = \frac{A_2' \sqrt{2g}}{\sqrt{1 - \frac{(A_2')^2}{(A_1')^2}}} \sqrt{\rho' (p_1' - p_2')} \tag{A13}$$

Equation (A13) is the theoretical equation for the flow of an incompressible fluid through a venturi, a flow nozzle, or an orifice. (In the case of the sharp-edged orifice, the pressure p_2' is considered to be taken at or near the vena contracta.)

For application to an actual venturi, flow nozzle, or orifice, equation (A13) must be multiplied by the coefficient of discharge. Two coefficients are commonly used: C, which does not include the velocity of approach factor $\sqrt{1 - (A_2')^2/(A_1')^2}$, and K, which includes the velocity of approach factor and is equal to $C/\sqrt{1 - (A_2')^2/(A_1')^2}$. Because it has been found convenient to use the letter K to represent other constants, C' has been used in this report to represent the coefficient of discharge with the velocity of approach factor included and a subscript that identifies the particular metering element to which the coefficient applies, has been used.

APPENDIX B

SYMBOLS

The following symbols are used in this report. Symbols without primes pertain to compressible fluids, whereas those with primes pertain to incompressible fluids.

A_f, A_f'	area of fixed restriction in compensation system
A_v, A_v'	area of variable restriction in compensation system
A_1, A_1'	area at entrance to metering element
A_2, A_2'	area at minimum section of metering element
C, C'	coefficient of discharge of metering element
C_f, C_f'	coefficient of discharge of fixed restriction in compensation system
C_v, C_v'	coefficient of discharge of variable restriction in compensation system
g	acceleration due to gravity
P_0, P_0'	total pressure at stagnation point
p_v, p_v'	variable pressure in compensation system
p_1, p_1'	static pressure at entrance to metering element
p_2, p_2'	static pressure at minimum section of metering element
R	gas constant
T_0	total temperature at stagnation point
T_2	static temperature at minimum section of metering element
V_1, V_1'	velocity at entrance to metering element
V_2, V_2'	velocity at minimum section of metering element
W, W'	fluid-flow rate

W_1, W_1' fluid-flow rate through compensation system

γ ratio of specific heats

ρ' density of incompressible fluid

ρ_0 density at stagnation point

ρ_1 density at entrance to metering element

ρ_2 density at minimum section of metering element

$\rho_x = p_2/RT_0$

$\rho_y = p_v/RT_0$

$$K = \frac{(0.985)^2 (W')^2 C^2}{R \rho' W^2 (C')^2}$$

$K_1 = KR$

$$K_2 = \frac{A_2{}^2 K_1}{(A_2')^2}$$

$$K_3 = \frac{C_f A_f}{C_v}$$

$$K_3' = \frac{C_f' A_f'}{C_v'}$$

$K_4 K_5 = K$

REFERENCE

1. Otto, Edward W.: Analysis of Accuracy of Gas-Filled Bellows for Sensing Gas Density. NACA TN No. 1538, 1948.

TABLE I - ALTITUDE

<table>
<tr><td></td><td colspan="2">$A_2 = f(T_0)$</td><td colspan="2">$A_2' = f(T_0)$</td></tr>
<tr><td rowspan="2">$A_2 = f(p_2)$</td><td colspan="2" rowspan="2">[1] $A_2 = A_2' \sqrt{\frac{1}{K_1 \rho_x}}$</td><td>$A_2 = f(p_2)$</td><td>$A_2' = f(T_0)$</td></tr>
<tr><td>[1] $A_2 = \sqrt{\frac{1}{K_4 p_2}}$</td><td>[2] $A_2' = \sqrt{\frac{K_5}{T_0}}$</td></tr>
<tr><td rowspan="2">$A_2' = f(p_2)$</td><td>$A_2' = f(p_2)$</td><td>$A_2 = f(T_0)$</td><td colspan="2" rowspan="2">[2] $A_2' = A_2 \sqrt{K_1 \rho_x}$</td></tr>
<tr><td>[2] $A_2' = \sqrt{K_4 p_2}$</td><td>[1] $A_2 = \sqrt{\frac{T_0}{K_5}}$</td></tr>
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<tr><td>[3] $A_v = K_3' A_2' \sqrt{\frac{1}{K_4 p_2 - (A_2')^2}}$
[4] $A_v = K_3' A_2' \sqrt{\frac{1}{K_4 p_2}}$</td><td>[1] $A_2 = \sqrt{\frac{T_0}{K_5}}$</td><td>[3] $A_v = K_3' \sqrt{\frac{1}{K_4 A_2^2 p_2 - 1}}$
[4] $A_v = \frac{K_3'}{A_2} \sqrt{\frac{1}{K_4 p_2}}$</td><td>[2] $A_2' = \sqrt{\frac{K_5}{T_0}}$</td></tr>
<tr><td rowspan="2">$(P_0 - p_2)_c = f(p_2)$</td><td>$(P_0 - p_2)_c = f(p_2)$</td><td>$A_2 = f(T_0)$</td><td>$(P_0 - p_2)_c = f(p_2)$</td><td>$A_2' = f(T_0)$</td></tr>
<tr><td>[5] $A_v = K_3 \sqrt{\frac{K_4 p_v}{(A_2')^2 - K_4 p_2}}$
[6] $A_v = K_3 \sqrt{\frac{K_4 p_2^2}{p_v\left((A_2')^2 - K_4 p_2\right)}}$
[7] $A_v = \frac{K_3}{A_2'} \sqrt{K_4 p_v}$</td><td>[1] $A_2 = \sqrt{\frac{T_0}{K_5}}$</td><td>[5] $A_v = K_3 A_2 \sqrt{\frac{K_4 p_v}{1 - K_4 A_2^2 p_2}}$
[6] $A_v = K_3 A_2 \sqrt{\frac{K_4 p_2^2}{p_v(1 - K_4 A_2^2 p_2)}}$
[7] $A_v = K_3 A_2 \sqrt{K_4 p_v}$</td><td>[2] $A_2' = \sqrt{\frac{K_5}{T_0}}$</td></tr>
</table>

[1]See fig. 1.
[2]See fig. 2.
[3]See figs. 3(a) and 3(b).
[4]See figs. 3(c) and 3(d).
[5]See fig. 4(a).
[6]See fig. 4(b).
[7]See figs. 4(c) and 4(d).

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COMPENSATION EQUATIONS

<table>
<tr><td colspan="2">$(p_1' - p_2')_c = f(T_0)$</td><td colspan="2">$(P_0 - p_2)_c = f(T_0)$</td></tr>
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<tr><td>${}^1A_2 = \sqrt{\frac{1}{K_4 p_2}}$</td><td>${}^3A_v = K_3' A_2' \sqrt{\frac{T_0}{K_5 - T_0 (A_2')^2}}$
${}^4A_v = K_3' A_2' \sqrt{\frac{T_0}{K_5}}$</td><td>${}^1A_2 = \sqrt{\frac{1}{K_4 p_2}}$</td><td>${}^5A_v = K_3 \sqrt{\frac{K_5 p_v}{p_2((A_2')^2 T_0 - K_5)}}$
${}^6A_v = K_3 \sqrt{\frac{K_5 p_2}{p_v((A_2')^2 T_0 - K_5)}}$
${}^7A_v = \frac{K_3}{A_2'} \sqrt{\frac{K_5 p_v}{p_2 T_0}}$</td></tr>
<tr><td>$A_2' = f(p_2)$</td><td>$(p_1' - p_2')_c = f(T_0)$</td><td>$A_2' = f(p_2)$</td><td>$(P_0 - p_2)_c = f(T_0)$</td></tr>
<tr><td>${}^2A_2' = \sqrt{K_4 p_2}$</td><td>${}^3A_v = K_3' \sqrt{\frac{T_0}{K_5 A_2^2 - T_0}}$
${}^4A_v = \frac{K_3'}{A_2} \sqrt{\frac{T_0}{K_5}}$</td><td>${}^2A_2' = \sqrt{K_4 p_2}$</td><td>${}^5A_v = K_3 A_2 \sqrt{\frac{K_5 p_v}{p_2(T_0 - K_5 A_2^2)}}$
${}^6A_v = K_3 A_2 \sqrt{\frac{K_5 p_2}{p_v(T_0 - K_5 A_2^2)}}$
${}^7A_v = K_3 A_2 \sqrt{\frac{K_5 p_v}{p_2 T_0}}$</td></tr>
<tr><td colspan="2" rowspan="2">${}^3A_v' = K_3' \sqrt{\frac{1}{K_2 \rho_x - 1}}$
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<tr><td>${}^3A_v = K_3' A_2' \sqrt{\frac{1}{K_4 p_2 - (A_2')^2}}$
${}^4A_v = K_3' A_2' \sqrt{\frac{1}{K_4 p_2}}$</td><td>${}^5A_v = K_3 A_2 \sqrt{\frac{K_5 p_v}{p_2(T_0 - K_5 A_2^2)}}$
${}^6A_v = K_3 A_2 \sqrt{\frac{K_5 p_2}{p_v(T_0 - K_5 A_2^2)}}$
${}^7A_v = K_3 A_2 \sqrt{\frac{K_5 p_v}{p_2 T_0}}$</td></tr>
<tr><td>$(P_0 - p_2)_c = f(p_2)$</td><td>$(p_1' - p_2')_c = f(T_0)$</td><td colspan="2" rowspan="2">${}^5A_v = K_3 \sqrt{\frac{K_2 p_v \rho_x}{p_2(1 - K_2 \rho_x)}}$
${}^6A_v = K_3 \sqrt{\frac{K_2 p_2 \rho_x}{p_v(1 - K_2 \rho_x)}}$
${}^7A_v = K_3 \sqrt{K_2 \rho_y}$</td></tr>
<tr><td>${}^5A_v = K_3 A_2 \sqrt{\frac{K_4 p_v}{1 - K_4 A_2^2 p_2}}$
${}^6A_v = K_3 A_2' \sqrt{\frac{K_4 p_2^2}{p_v(1 - K_4 A_2^2 p_2)}}$
${}^7A_v = K_3 A_2 \sqrt{K_4 p_v}$</td><td>${}^3A_v = K_3' A_2' \sqrt{\frac{T_0}{K_5 - T_0 (A_2')^2}}$
${}^4A_v = K_3' A_2' \sqrt{\frac{T_0}{K_5}}$</td></tr>
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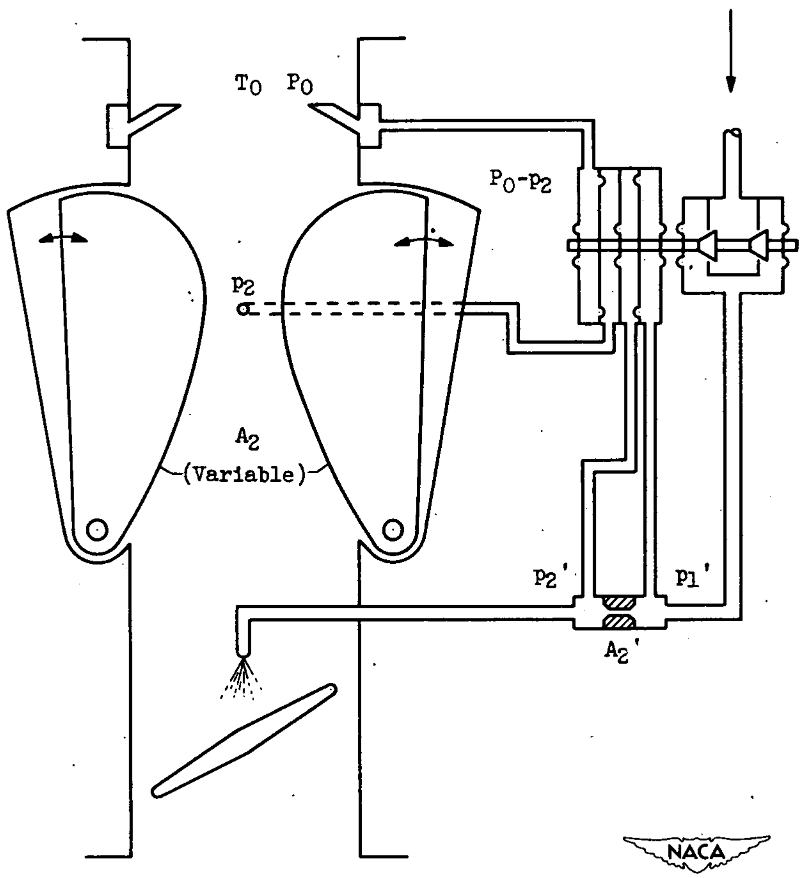


Figure 1. - Schematic diagram of carburetor with compensation by variation of venturi area.

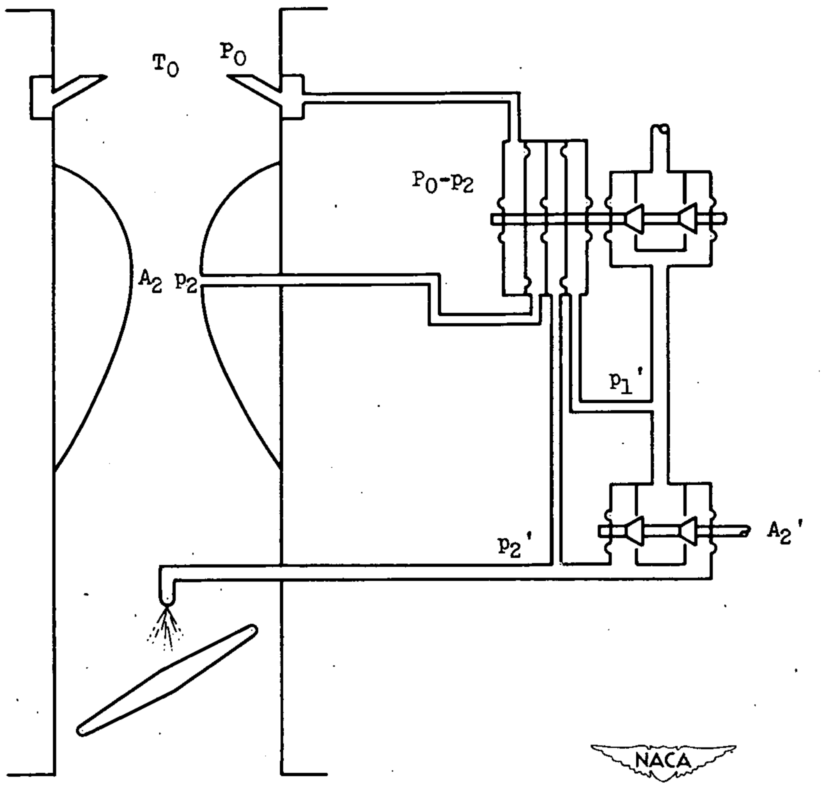
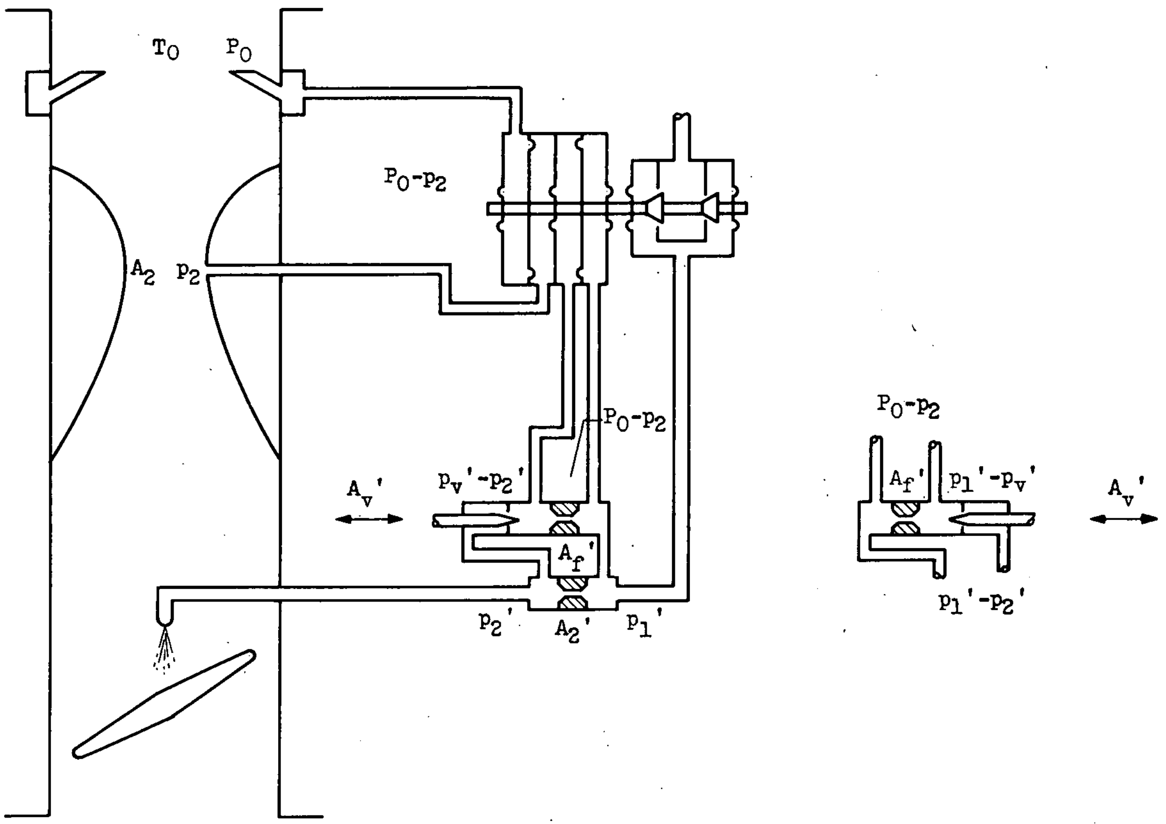


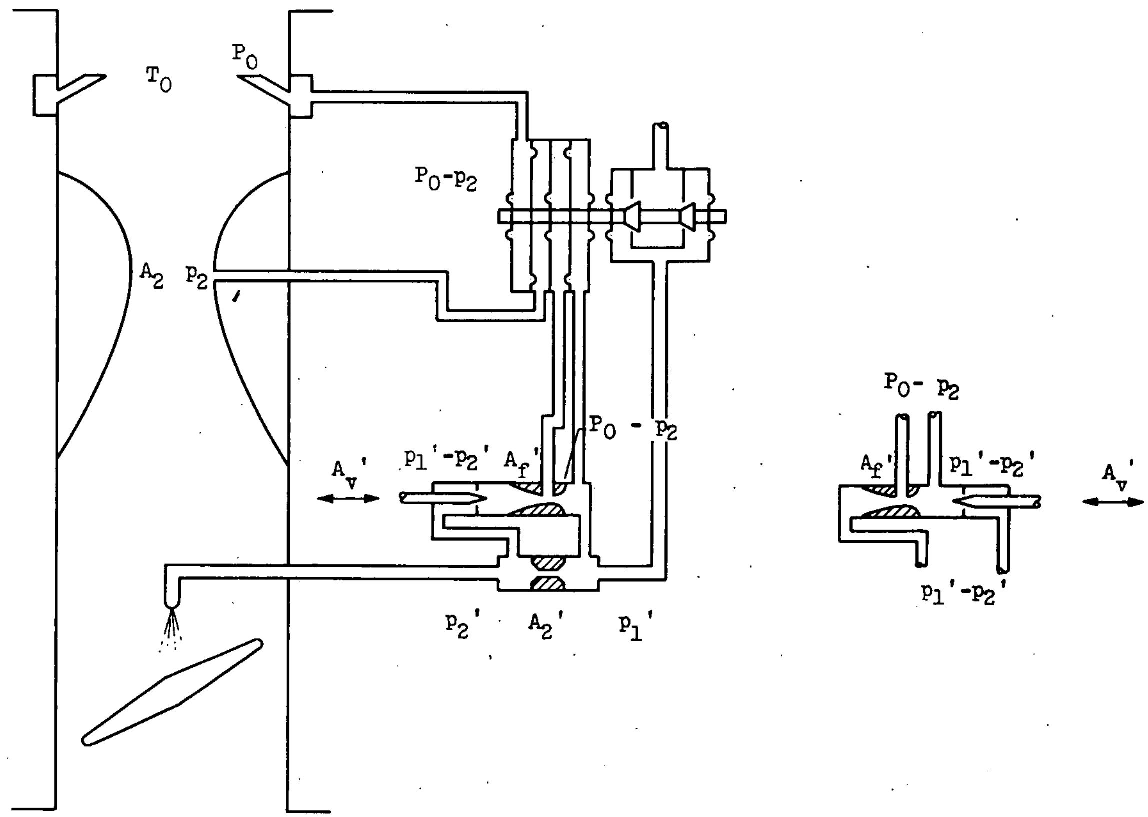
Figure 2. - Schematic diagram of carburetor with compensation by variation of fuel-jet area.



(a) Method 1.

(b) Method 2.

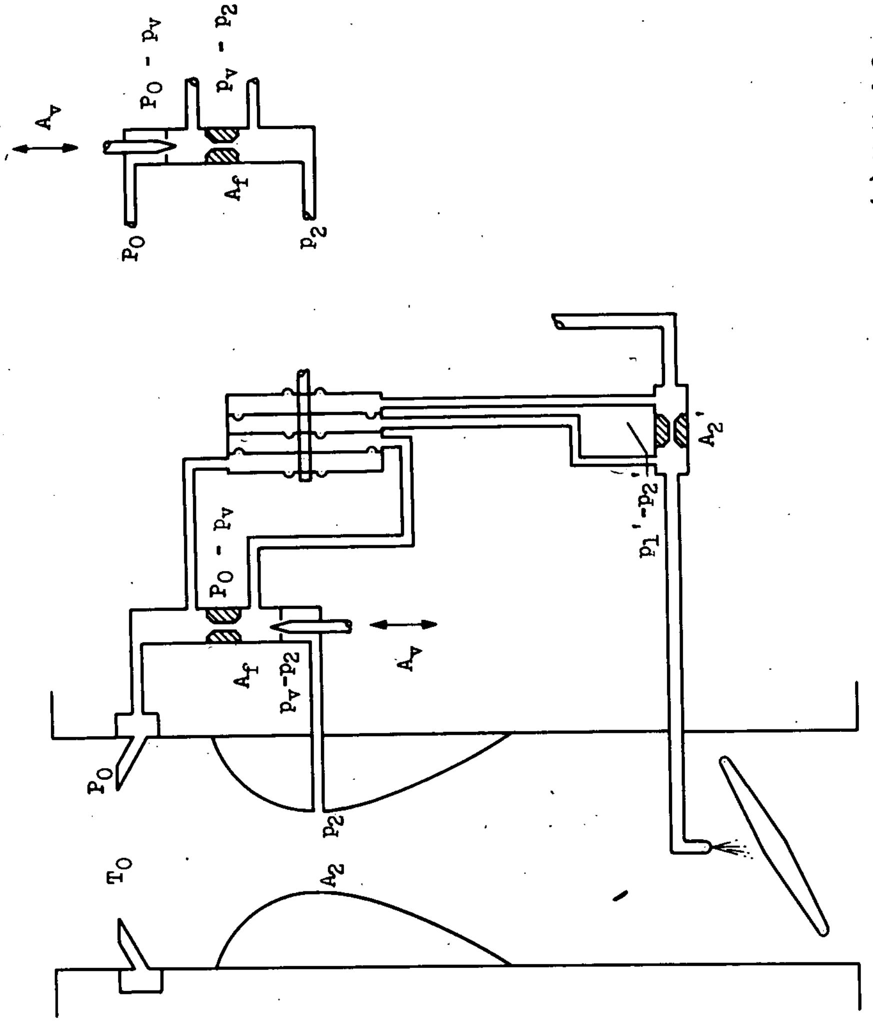
Figure 3. - Schematic diagram of carburetor with compensation by variation of effective fuel-jet pressure drop.



(c) Method 3.

(d) Method 4.

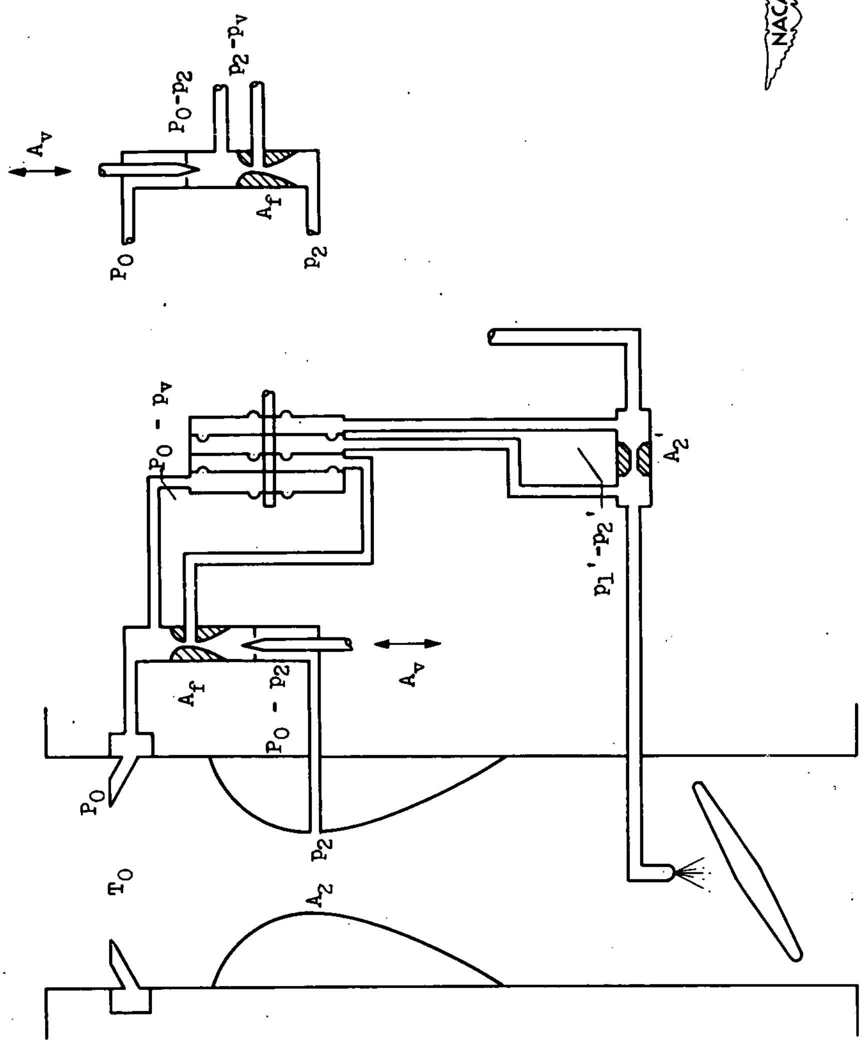
Figure 3. - Concluded. Schematic diagram of carburetor with compensation by variation of effective fuel-jet pressure drop.



(a) Method 1.

(b) Method 2.

Figure 4. - Schematic diagram of carburetor with compensation by variation of effective venturi pressure drop.



(c) Method 3.

(d) Method 4.

Figure 4. - Concluded. Schematic diagram of carburetor with compensation by variation of effective venturi pressure drop.

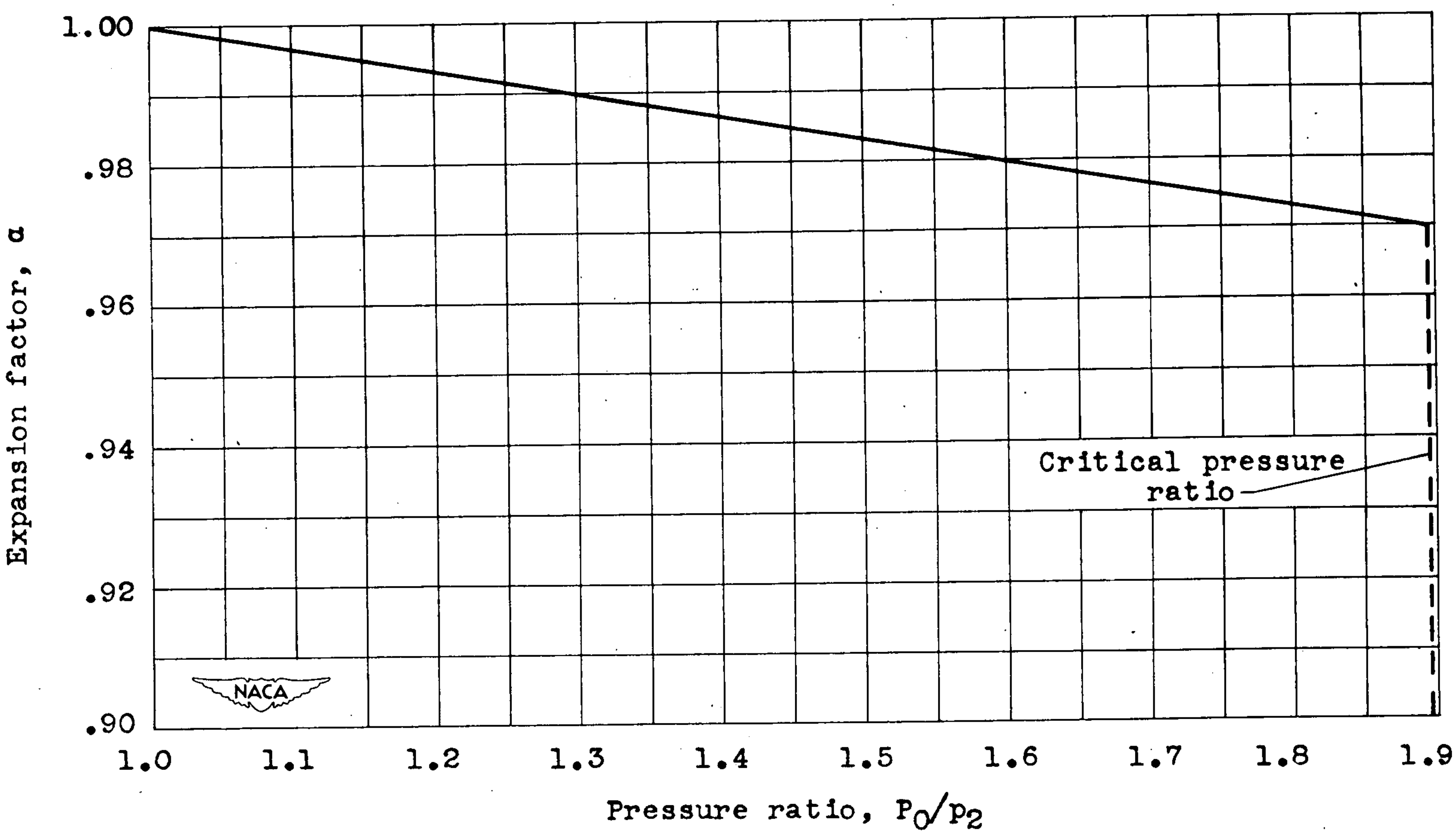


Figure 5. - Effect of pressure ratio on expansion factor at specific-heat ratio of 1.4.