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Investigation Into the Flow Phenomenon of a Carbureted Engine

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INVESTIGATION INTO THE FLOW PHENOMENON OF A CARBURETED ENGINE

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Definitions

Air-Fuel (air/fuel) Ratio – the mass flow rate of air divided by the mass flow rate of fuel, lb/s per lb/s (Obert, 1968, p. 48).

Brake specific fuel consumption (bsfc) – mass of fuel consumed divided by horsepower generated, lb_f/hp.

Lean mixture – an air to fuel ratio greater than 15:1 (Lewis, 1962, pp. 471-472).

Rich Mixture – an air to fuel ratio less than 15:1 (Lewis, 1962, pp. 471-472).

Two phase flow – transport of liquid by a gas.

Introduction

The modern racing engine relies on the combustion of fuel and air to produce linear motion, which propels the racecar towards the finish line. The most common method for supplying the air and fuel mixture to the cylinders of the current racing engine is a carburetor and wet flow intake manifold. As the piston of an engine moves downward in the cylinder bore during the intake stroke air is pulled into the engine causing the pressure in the venturi of the carburetor throat to drop below that of atmospheric as air flows through it (Lichty, 1967). When the air flows through the carburetor, the pressure at the jet is reduced below atmospheric thereby causing fuel to enter the air stream through the fuel jet. Once the stream of fuel enters the carburetor throat, it is torn into various size droplets.

So that it may be understood, the sport of drag racing involves propelling a vehicle as quickly as possible for 1320 feet or one quarter of a mile. During these conditions, the engines in the vehicles are subjected to extreme situations such as very rich air-fuel ratio (air/fuel ratio) mixtures, less than 14 $lb_{m,air}/lb_{m,fuel}$, and rotational speeds in excess of 6000 revolutions per minute (RPM). Both of these conditions may lead to very poor mixture situations for the fuel in the intake tract. Because of the overly rich conditions necessary for the production of maximum power, air/fuel ratios in the range of 12 to 13 $lb_{m,air}/lb_{m,fuel}$, it is possible that the fuel has a tendency to collect in the intake runner and riser and cause the droplet size to increase thus slowing the atomization quality (Lichty, 1967).

High engine rotational speeds hinder the atomization of fuel by decreasing the amount of time that the fuel is located in the intake tract of the engine. Many racing engines consume air at rates in excess of 750 cubic feet per minute (cfm) at rotational speeds in excess of 6000 revolutions per minute. These speeds relate to an intake event every 0.02 seconds. Since complete vaporization of the fuel is necessary for the fuel mixture to completely combust, some of the fuel must vaporize inside the combustion chamber. This slows the combustion process and therefore decreases power output.

Components of Induction System

Carburetor Fundamentals

The carburetor used on modern racing engines consists of a complex assembly of components. The type of carburetor currently used in the United States is of the jet type (Lind, 1920). In its most elementary form it consists of a converging-diverging nozzle, fuel bowl, pressure-equalizing passage, jet, fuel discharge passage and throttle blade as depicted in Figure 1 (Heywood, 1988).

Four-barrel carburetors consist of two primary and two secondary barrels with throttle blades on two air/fuel operating the barrels in parallel. At low engine speeds and moderate engine loads, the air flows through the primary barrels and into the intake manifold. At higher engine speeds and loads the air and fuel flow directly through both the primary and secondary barrels. The secondary barrels can be of larger cross sectional area than that of the primary barrels and begin to open when the airflow exceeds 50% of the maximum engine airflow when using vacuum operated secondary barrels. As the

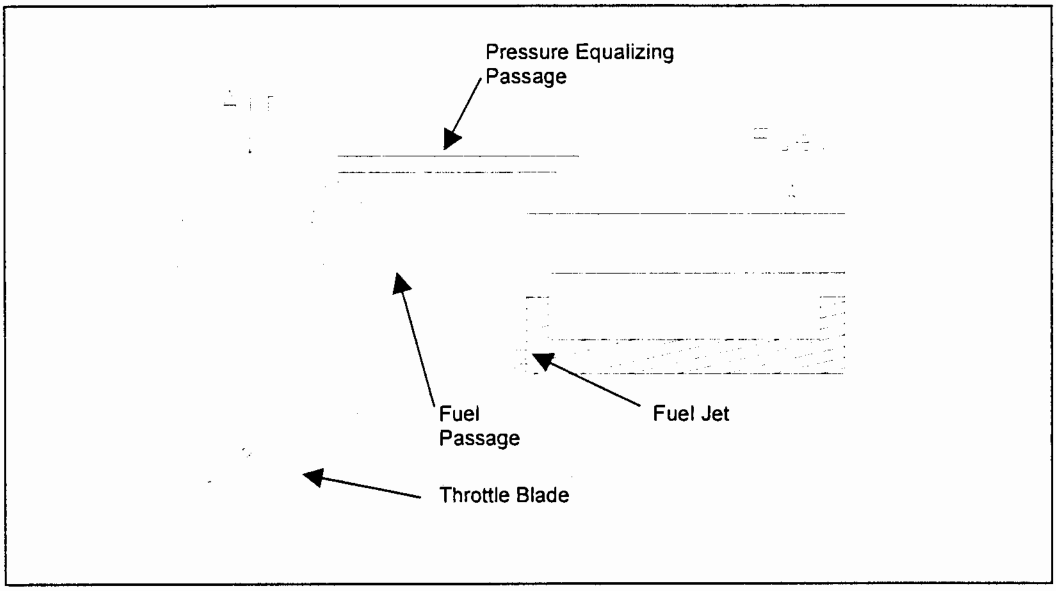

Figure 1. Schematic of jet type carburetor.

engine vacuum decreases the amount of force exerted on the secondary barrel dashpot is decreased and the air valve is allowed to open allowing air to flow through the barrels. A racing engine usually incorporates the use of mechanically operated secondary barrels. A linkage connecting the secondary throttle shaft to the primary throttle shaft will cause these barrels to become operative once the throttle has opened a predetermined amount. The point at where the secondary barrels begin to open can be adjusted to accommodate different loading scenarios (Urich & Fisher, 1976). The use of carburetors with parallel barrels is a common way of maintaining part load throttle response, high volumetric efficiency at wide open throttle and low engine height as higher load demands are placed on the engine.

Carburetor Operation

As the air flows through the carburetor, the liquid fuel enters the air stream through the fuel discharge tube due to the dynamic pressure drop in the carburetor from the intake stroke of the engine (Annand, 1988; Heywood 1988; Lind, 1920). A small orifice opening in the fuel discharge tube delivers the liquid fuel into the moving air stream where it is atomized and moved by the air stream past the throttle plates and into the engine (Heywood, 1988; Lind 1920, Lichty 1967). The reason that fuel droplets are formed is that the rapidly moving air-stream tears the fuel threads that are being emitted from the jet orifice into varying size drops (see Figure 2) (Nightingale, 1990). Since the object of the carburetor is to prepare the fuel for combustion, a smaller orifice diameter

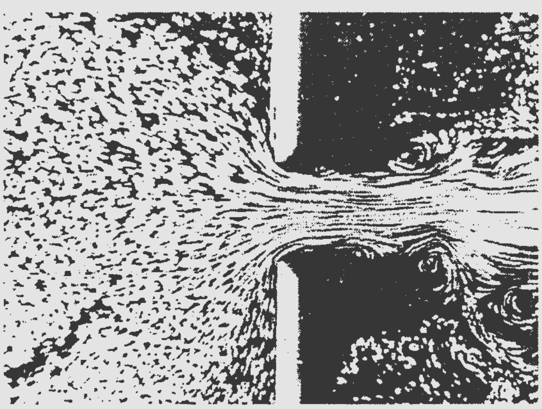

Figure 2. Image showing flow exiting an orifice. This would compare to fuel exiting a fuel jet and entering the air stream. Note. From Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization (p. 72), by The Japan Society of Mechanical Engineers, 1988, New York: Pergamon. Copyright 1988 by Pergamon. Reprinted with permission.

used in the fuel discharge tube will expose a greater surface area to volume ratio of the tube and this should lead to better atomization of the fuel (Streeter & Lichty, 1933).

Streeter, Lichty (1933) and Annand (1988) agree that the fuel and air mixture, as it leaves the carburetor, will consist of partly evaporated fuel, a mist of fine particles and a mixture of heavier particles. The fuel is atomized as it enters the high-speed (>100 m/s) air stream from the fuel discharge tube (Heywood, 1988). Lind (1920) lists four key factors for determining the quantity of liquid fuel which will flow through a fuel jet as: " (a) The viscosity of the fuel, (b) the temperature of the fuel, (c) the shape of the orifice or nozzle, and (d) the effective head actuating at the orifice" (p. 65). As the amount of power that can be produced by the engine is directly related to the amount of fuel that can be ingested through the carburetor, these four factors are the main determinants of engine power output for any given fuel orifice size.

There has been some disagreement where actual fuel evaporation begins. Annand (1988) states that little fuel evaporation occurs in the carburetor at the point of delivery but, rather, begins in the intake manifold. Heywood (1988) contends that evaporation begins in the carburetor and is continued through the intake manifold. The amount of heat transferred to the manifold and carburetor from the engine needed to vaporize the fuel is directly related to the droplet size and the amount of liquid contained in the wall film (Urich & Fisher, 1976).

Ancillary Carburetor Systems

There are several ancillary systems with the carburetor, the power enrichment system and accelerator pump, that allow it to perform under the changing demands of the internal combustion engine. Since airflow levels can change dramatically from no load to full load, airflow at wide open throttle can be 30 to 70 times the airflow at idle, a power enrichment system and an accelerator pump are necessary requirements of the modern carburetor (Heywood, 1988). The power enrichment system, enrichment valve and passages, provides additional fuel to enrich the fuel-air mixture as maximum engine speed is reached. This allows the engine to produce maximum power by ensuring all cylinders receive the minimum amount of fuel required for maximum power. This enrichment of the fuel-air mixture is especially important in drag racing, as it is imperative that the engine is able to make full power at all times. If a cylinder were to become too lean, air to fuel ratio greater than 14 $lb_{m,air}/lb_{m,fuel}$, detonation could occur in that cylinder and cause catastrophic engine failure. Detonation is where the combustion process occurs without control. The usual combustion process is a controlled flame traveling through the cylinder that does not completely burn and raise cylinder pressures until the piston has changed directions. Detonation is an actual explosion of the gas mixture, which causes cylinder pressures to rise rapidly causing damage from the still upward movement of the piston.

The accelerator pump provides a charge of fuel as the throttle plates are opened. The problem caused by rapidly opening the throttle plates is that the fuel air mixture entering the cylinder temporarily becomes leaner due to the time lag of fuel entering the carburetor air stream and the fuel flow into the cylinder past the inlet valve. The accelerator pump provides additional fuel into the air stream to compensate for this leaning effect.

Most carburetors have a small booster venturi located within the larger main venturi (see Figure 3). The fuel is better atomized through the smaller booster due to its higher airflow. The higher flow rate with the double venturi system is caused by a pressure drop of almost twice that of a single venturi of the same flow area. The overall flow coefficient of the multiple venturi system is lower than that of an equal cross sectional area single venturi. Therefore, some decrease in air velocity is tolerated by the operator to increase the flow coefficient by enlarging the main venturi throat area. Since

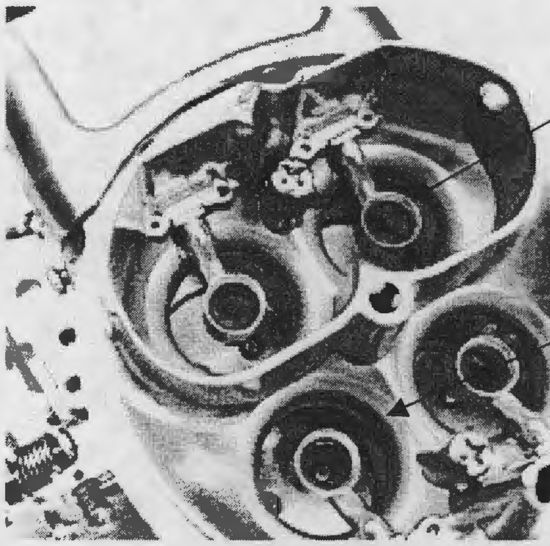

Figure 3. Image showing double venturi in throat of Street Demon Carburetor. Note. From Demon Carburetion Technical Information. Copyright 1999 GPT300. Reprinted with permission.

the booster is located centrally in the larger booster, the fuel air mixture exiting the booster venturi is a more homogenous mixture than that of a single venturi system.

Evolution of Carburetor Design

Demise of the Original Equipment Carburetor

In the late Seventies the demise of the carburetor was discussed in magazines and journals due to the inefficiencies and need to better control the air to fuel ratio to meet ever tightening environmental regulations (Bohacz, 2000a; Bohacz, 2000b). This was not a short transition as the automotive manufacturer's tried to make the carburetor continue to function in this new world of increased fuel economy and lower emissions. Through the early Eighties the automotive manufacturer's tried increasing the efficiency of the carburetor through the use of electronic feedback and oxygen sensors. Since this was a closed loop system it did function at keeping the mixture regulated at the stoichiometric air to fuel ratio of 14.7 $lb_{m,air}/lb_{m,fuel}$ but, due to its wet flow design it had a poor corrective response time (Bohacz, 2000a). Due to this reason automotive manufacturers have changed induction design from carburetion to electronic fuel injection to raise the fuel economy and lower the emissions of production engines. However, due to the cost and complexity of these systems most hobbyists and racers have had to use carburetors that have basically not changed since the origination of the jet type carburetor.

Demon Carburetion Design Advantage

Demon Carburetion has introduced a new line of modular carburetors that are using the latest in manufacturing techniques to produce a carburetor that rivals electronic fuel injection for fuel delivery performance (Bohacz, 2000b). Through the use of a new manufacturing process called Concentracast, the main body that houses the main venturi is devoid of the common casting and core shift that has hindered air flow in carburetors for years. As the air is entering the venturi any imperfection on the wall of the casting inhibits flow by inducing turbulence into the air stream. Also, by using the Concentracast method the carburetor venturis are consistent from one carburetor to the next and also from one barrel of the carburetor to another. Bohacz adds that another advantage this carburetor has is a patented air entry design. This design incorporates a more contoured air inlet that allows for a more laminar flow entering the carburetor, which reduces pumping losses and provides a straight inlet into the main and booster venturis.

The carburetor also uses other components that are superior to previous high performance carburetors (Bohacz, 2000a). The metering block, which is, located between the float bowl and the carburetor main body houses that fuel enrichment circuit, metering jets and idle circuit. In other high performance carburetors this is a cast piece, which can lead to porous part. This porosity can lead to leaks between the metering passages in the carburetor. These leaks lead to poor tuning ability and inconsistent performance. The new Demon Carburetion line employs a billet-metering block that eliminates the porosity leaks in the metering circuits. This leads to better tuning and higher performance through increased metering signal. The carburetors also feature a four corner idle circuit which, Bohacz states, creates a better fuel distribution system and improves idle quality by not forcing the front two barrels of the carburetor to feed all of the cylinders of the engine with fuel through the front half of the intake plenum (2000b).

Demon Carburetion Performance Advantage

Bohacz (2000b) notes that testing was performed with a Race Demon™ 750 carburetor that was pulled from the production line and bolted to a 468 cubic inch engine. With no adjustments other than idle speed allowed during the testing, a ETAS wide band linear air/fuel meter was installed to monitor the performance of the carburetor along with the dynamometer's data acquisition system. The engine started immediately and a part throttle and full throttle dynamometer test were performed. The engine produced 710 horsepower but as Bohacz states the most impressive accomplishment of the carburetor was the fuel curve that the carburetor produced. Most production high performance carburetors produce peaks and valleys on the fuel curve at various points in the speed band. This carburetor did not show any of these characteristics but rather, had a smooth and linear fuel curve rivaling some of the best electronic fuel injection systems. This is accomplished because the Demon carburetor does a better job at emulsifying and atomizing the fuel exiting the carburetor than any of the other high performance carburetors on the market today.

Intake Manifold Fundamentals

Once the flow exits the carburetor it enters the fuel/air distribution system, the intake manifold. The job of the intake manifold is to take the mixture consisting of air, a small portion of gasoline vapor and fuel particles and distribute it to the various cylinders in the engine (Streeter & Lichty, 1933). Intake manifolds typically consist of a plenum, the chamber located directly under the carburetor, with runners leading to each cylinder of the engine (Heywood, 1988). The manifold, ideally, should take the mixture as supplied by the carburetor and distribute it evenly between each of the engines cylinders (Annand, 1988).

The atomization process that began in the carburetor is continued in the intake manifold (Heywood, 1988). The atomization process includes any evaporation that began in the carburetor. Heating of the intake manifold walls aids in the evaporation of the fuel as the air/fuel mixture flows along the port walls of the manifold (Annand, 1988). Annand also adds that the heat input to the manifold is usually limited to minimize the reduction in charge density, which leads to better performance through higher fuel densities. Lichty (1939) notes that the mixture condition at the engine cylinder depends on the flow velocity, the design of the manifold, and the amount of heat added between the carburetor and manifold to evaporate any liquid fuel flowing on the walls of the manifold.

Performance Manifold Choices

There are many manifolds available through the aftermarket parts industry today to fit a wide range of performance needs. These manifolds range in design from near original equipment design to high rotational speed, pure race manifolds. The decision as to what manifold to use is based on several key criteria. These include: desired operating range for engine speed, amount of hood clearance available, intended use of vehicle and emissions requirements (Edelbrock, 2000).

For applications requiring higher than stock torque at low rotational speeds modified original equipment manifolds, such as Figure 4, offer increased torque at low

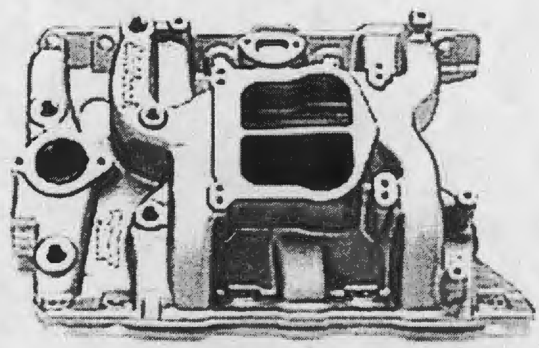

Figure 4. An Original Equipment Manufacture dual plane manifold. Note. From Edelbrock Performance Catalog Catalog. Copyright 2000 Edelbrock Corporation. Reprinted with permission

rotational speed and still remain 50 state emissions legal (Edelbrock, 2000). The increase in torque is attributed to better-optimized runner design, which also leads to better throttle response for off-idle to mid range rotational speeds. The recommended operating range for this manifold design is from idle to 5500 rpm.

The next step from on original equipment replacement is a high-rise dual plane manifold such as the Edelbrock Performer RPM™ manifold (see Figure 5) (Edelbrock,

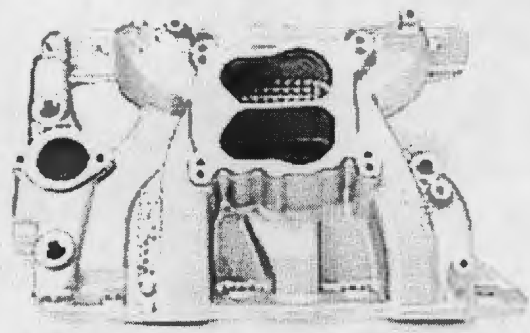

Figure 5. A high performance dual plane manifold. Notice the straighter path from the carburetor throttle bores to the cylinder head port openings. Note. From Edelbrock Performance Catalog. Copyright 2000 Edelbrock Corporation. Reprinted with permission

2000). This manifold design features raised runner floors that lead to higher air flow potential over the original equipment manifold. This potentially leads to higher rotational speed operation and higher power production. These manifolds are recommended for high performance street engines that are not emissions legal. The operating range of these manifolds is from 1500 to 6500 rpm.

Once the demand for more horsepower is realized the next step for the racing enthusiast is a single plane manifold such as the Torker II™ manifold (see Figure 6) (Edelbrock, 2000). This is a single plane low-rise manifold that is used in high rotational speed, high-performance street applications. One of the advantages of this manifold is that it offers higher airflow potential and a higher operating range while still providing

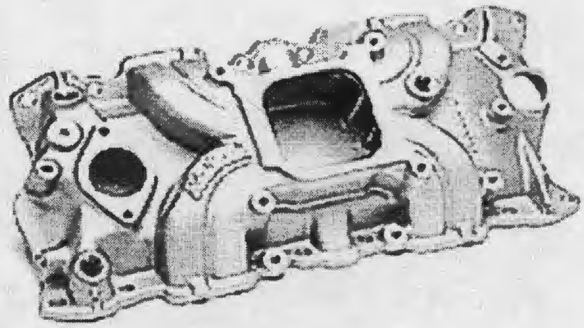

Figure 6. Single plane, low-rise, high performance intake manifold. Note. From Edelbrock Performance Catalog. Copyright 2000 Edelbrock Corporation. Reprinted with permission

adequate hood clearance for most vehicles. The recommended operating range for this manifold is from 2500 to 6500 rpm.

If hood clearance is not an issue and high rotational speed is required of the intake manifold for the engine to perform, than there are two options available. The first option would be a single plane, high-rise manifold (see Figure 7) (Edelbrock, 2000). These manifolds are designed for maximum power at high rotational speeds. One of the advantages of this manifold over the other designs is the equality of runner length among

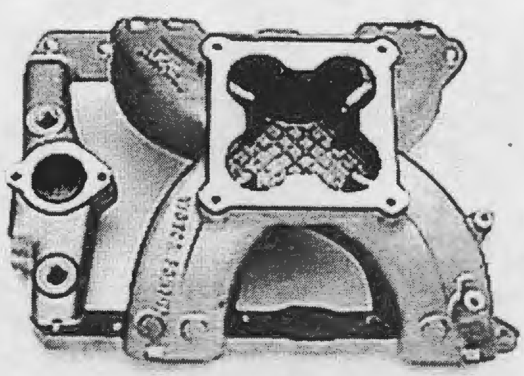

Figure 7. High-rise, single plane performance manifold. Notice the plenum dividers to divert airflow to the appropriate cylinder and the curvature of the runner. Note. From Edelbrock Performance Catalog. Copyright 2000 Edelbrock Corporation. Reprinted with permission

all of the runners. By keeping the runner length equal each cylinder is delivered the same velocity airflow. This helps to more evenly distribute the fuel to the cylinders thus tightening the air-fuel requirements, as there is not any compensation for any one cylinder. The operating range of this manifold design is from 3500 to 8500+ rpm.

The second option is a dual carburetor, tunnel ram manifold (Edelbrock, 2000). Figure 8 clearly shows why this manifold is used in most professional forms of drag

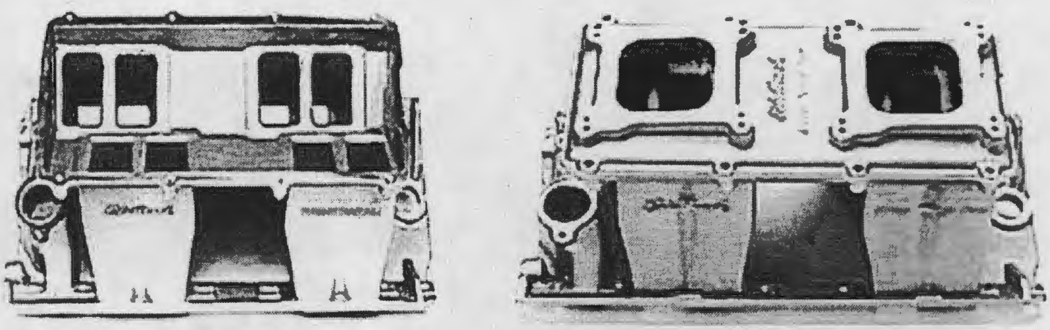

Figure 8. Tunnel ram manifold used in high performance drag racing without and with carburetor base attached. These manifolds use two carburetors so that each cylinder is fed an air-fuel mixture from one barrel of the carburetor. Note. From Edelbrock Performance Catalog. Copyright 2000 Edelbrock Corporation. Reprinted with permission

racing when using naturally aspirated engines, as it provides a straight path from the carburetor to the intake valve in the cylinder head. Also, the height of these manifolds tends to produce a ram effect due to the tuning of the runner length. This is caused by the momentum of the air continuing to feed the cylinder after the piston has ceased downward movement and is dwelling at the bottom of its travel allowing the intake valve to stay open longer therefore allowing more air and fuel into the cylinder. These manifolds are intended for drag racing only and are for operation in the 6500 to 10,000 rpm range.

Fuel/Air Mixture

Formation of Mixture

Internal combustion engines need a properly prepared fuel-air mixture to attain maximum performance from a given amount of fuel and air (Heywood, 1988). The process of forming the mixture is combining subdivided particles or atomized fuel with air (Streeter & Lichty, 1933). Liquid fuel is atomized when it has been subdivided as small as possible with representative droplet diameters of 25 to 100 μm (Streeter & Lichty, 1933; Heywood, 1988). Fuel that is completely atomized presents the maximum amount of surface area to the air stream and the small drop sizes lead to evaporation (Streeter & Lichty, 1933). Annand (1988) gives the relationship for the maximum amount of vapor that air in the manifold can contain as:

$$(M_f/M_a)P_v/(P-P_v)$$

where:

M_f = molecular weight of fuel

M_a = molecular weight of air

P_v = vapor pressure of fuel

P = absolute pressure in manifold.

Annand concludes that the maximum possible ratio of fuel to air decreases as the throttle is closed.

The degree of atomization is a function of the square of the relative velocity (Streeter and Lichty, 1933). Heywood (1988) concurs and notes that secondary atomization of the fuel when it is entrained by the air at the throttle plate is dependent on the relative velocity of the air traveling past the throttle plate. The higher the velocity, the smaller the droplet size that will form. The smallest drops, < 10 μm, are formed as the air is accelerated past the throttle plate at part throttle loads due to the vacuum generated during the downward stroke of the engine piston. The atomized fuel leaving the carburetor is likely to impact the walls of the manifold and become a liquid film adhering to the walls of the manifold (Heywood, 1988; Shayler & Armstrong, 1988). Impaction on the walls is due to the mixture leaving the carburetor consisting mainly of large fuel droplets (Streeter & Lichty, 1933, Obert 1968; Taylor, 1985). The portion of the mixture consisting of fuel vapor and a fine mist of fuel, can both be carried by the air stream and therefore tend to follow the contours of the manifold. Under steady state operation the fuel is distributed onto the floor of the manifold riser, the portion of the manifold directly under the carburetor (Shayler & Armstrong, 1988).

The manner in which the fuel is distributed has a strong influence on cylinder-to-cylinder charge density as the heat input to the floor of the riser leads to evaporation of the liquid fuel. The amount of fuel accumulating on the floor of the manifold is determined by the rate of change of the fuel entering the manifold and the fuel departing the fuel puddle due to evaporation (Heywood, 1988). The amount of fuel entering the puddle is regulated by the metering function of the carburetor. Evaporation of the fuel is driven by the airflow across the puddle in addition to the heat input into the floor of the manifold. Heywood (1988) has developed an equation for determining the rate of change of fuel mass in the puddle as:

$$m_{f,p} = m_{f,\,in} - m_{f,\,out} = \chi m_{f,m} - m_{f,p}/\tau$$

where:

$m_{f,p}$ = mass of fuel in the puddle

$m_{f,m}$ = metered fuel flow rate

χ = fraction of the metered flow that enters the puddle

τ = characteristic time of reentrainment/evaporation process (p. 318).

Annand (1988) adds that at throttle positions above one-half of the brake mean effective pressure, there is always fuel puddled on the floor of the manifold. The mean effective pressure of an engine is defined as the work per cycle divided by the cylinder volume displaced per cycle. Heywood (1988) provides the following equation to determine the brake mean effective pressure of any engine as:

$$mep(lb/in^2) = \frac{P(hp)*396{,}000}{V_d N(rev/\min)}$$

where:

P = brake power generated

V_d = displacement of the engine

N = rotational speed of the engine (p. 50).

The reason a puddle is always present at this position is that the residence time of the fuel in the manifold is not long enough for evaporation to occur from either the heat input into the manifold or from forced convective mass transfer. However Annand (19880 contends that at positions below this point, the fuel will evaporate from the floor of the manifold. This has been observed using manifolds fitted with clear windows (1988).

Two Phase Flow

Since the internal combustion gasoline engine relies upon liquid fuel to supply the energy required to make power the study of the delivery of that fuel, involves the study of two-phase flow. Two-phase flow occurs when both a liquid and a gas are combined in a single flow field, such as liquid fuel droplets and atomized fuel and air. A pressure drop caused by the engine piston moving downward drives the mixture through the intake tract of the engine (Annand 1988). The governing equation for fluid flow through any flow passage can be given as:

$$v = c\sqrt{2gh}$$

where:

v = velocity of the fluid, feet/sec

c = discharge coefficient

g = acceleration due to gravity, 32.2 ft/sec/sec

h = head of fuel causing the flow, feet (Lichty & Streeter, 1933, p. 243).

Typical coefficient of discharge for the venturi of the carburetor is approximately 0.83 for flows above 145 feet per second (fps). The jet coefficient of discharge can range between 0.63 and 0.76 with a typical assumption of 0.70 for fuel jets with circular orifices. Streeter and Lichty (1933) give numerous factors that affect the coefficient of discharge when dealing with liquid fuels. These factors are: (a) " size of the orifice, (b) shape of the fuel orifice, (c) proportions of the orifice, (d) entrance to the orifice, (e) viscosity of the fuel, (f) temperature of the fuel, and (g) Rate of flow" (p. 245). Several of these factors correspond with the four rules of liquid fuel flow for determining the maximum amount of fuel that can flow through a carburetor jet. Thus, the rate of flow through the carburetor and manifold depends upon the displacement of the engine, the speed of the engine, the volumetric efficiency of the intake system and the size of the smallest portion in the intake tract. One typical assumption of two-phase flow is that the gaseous flow can be considered independent of the liquid flow but the liquid flow is dependent of the gaseous flow (Heywood, 1988).

Flow Around Bends

Since the entrained fuel droplets are much heavier than the air they are flowing in, bends pose a problem in the transport of the fuel to the cylinder (Heywood, 1988; Taylor 1985). The fuel and air flowing in an intake tract can attain velocities in excess of 300 fps and this tends to cause the fuel and air to separate in bends (Urich & Fisher, 1976). Heywood (1988) gives the equation for the formation of an individual droplet as:

$$(1/6\pi D^3{}_d\rho_f)a=m_dg-1/2(v_d-v_g)|\ v_d-v_g|\rho_gC_D(\pi D^2{}_d/4)$$

where:

D_d = droplet diameter

ρ_f and ρ_g = liquid and gas density

v_d and v_g = droplet and gas velocities

a = droplet acceleration

g = acceleration due to gravity

C_D = coefficient of drag = $27Re^{-0.84}$ for $6 < Re < 500$ (p. 317).

Heywood continues by stating that for droplets flowing around 90° bends those droplets less than 10µm in diameter tended to flow with the air-stream while most of the droplets larger than 25 µm impacted the wall.

Also, as the flow makes the turn around the bend in the manifold, there are several other factors playing a role in the degree of atomization in the fuel. When fluid flows around a bend, there is an area of separation directly after the bend (see Figure 9) (Ackeret, 1967). After the fluid separates from the wall of the manifold, it will return to the full cross sectional flow area if the width of the manifold runner is not expanding at

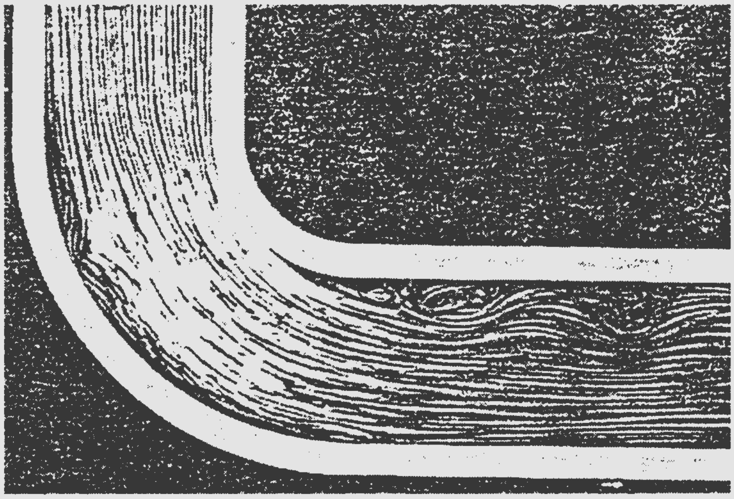

Figure 9. Image showing flow separation and eddy currents. Note. From Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization (p. 70), by The Japan Society of Mechanical Engineers, 1988, New York: Pergamon. Copyright 1988 by Pergamon. Reprinted with permission.

along its length. Ackeret notes the reason for this phenomenon is that the free streamlines or wakes cannot expand indefinitely and will therefore collide with the wall and the flow will reattach. However, this is not to say that there is no flow in the zone of separation as eddy current flow occurs in this region. As the flow makes the turn through the bend, the pressure of the fluid increases from the inner radius to the outer radius. This tends to cause a pool of liquid on the outer wall of the manifold (Lichty, 1939). Turning vanes help to direct the flow around the corner and inhibit the separation zone and inherent eddy currents. This is illustrated in Figure 10 (Ackeret, 1967; The Japan Society of Mechanical Engineers, 1988).

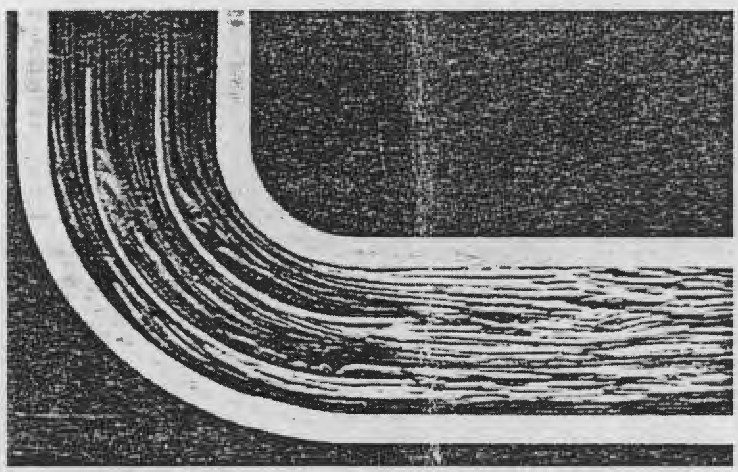

Figure 10. Image showing turning vanes leading to lack of flow separation and eddy currents. Note. From Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization (p. 70), by The Japan Society of Mechanical Engineers, 1988, New York: Pergamon. Copyright 1988 by Pergamon. Reprinted with permission.

To show the constructive and beneficial use of turning vanes, Ackeret discusses a series of three bends in a channel where the individual pressure loss in each bend is 1.3 %, however the overall loss of the system is 9.2 %. If turning vanes are added to the same system, the individual losses are reduced. Interestingly, using turning vanes causes the total loss to be less than but closer to the sum of the individual losses.

Since the duty of the intake system is to deliver the fuel air mixture to the cylinder of the engine, it is important to explore other flow phenomenon that occur in the system when attempting to alleviate the earlier problems of flow separation and pressure drop. One would think that a natural occurrence in the manifold would be to have all of the turns streamlined to help aid in redirecting the flow. However, as Lichty (1939) points out, any streamlining that increases the flow area reduces the velocity of the fluid and therefore helps to precipitate out any fuel particles that are too large to be carried by the slower moving fluid. Instead of streamlining the flow, he recommends having a sharp entrance from the riser into the runners, as this helps to tear the liquid film from the wall of the manifold. This can be seen in Figure 11 where the fluid makes a turn around a sharp corner as contrasted with Figure 9 where it is a streamlined bend.

Mixture Inconsistency

In the sport of drag racing it is important to provide the engine with a consistent

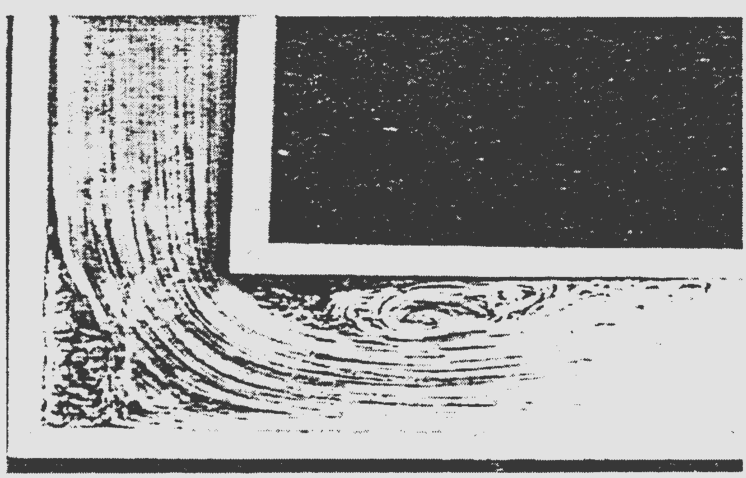

Figure 11. Image showing flow around a sharp bend with flow separation and eddy currents. Note. From Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization (p. 70), by The Japan Society of Mechanical Engineers, 1988, New York: Pergamon. Copyright 1988 by Pergamon. Reprinted with permission.

fuel mixture. Due to the nature of the sport, the engine is operating at a throttle position far more open than the half opened position that Annand (1988) refers to as generating a fuel puddle. This causes the engine to be presented with a wide array of fuel mixtures, which can lead to dangerous conditions such as catastrophic detonation.

The distribution of the fuel into the combustion chamber determines how effectively an engine will burn fuel (Harrow, 1977). Perfect distribution is defined as the condition of every cylinder receiving the same quality and quantity of fuel (Taylor & Taylor, 1966). Heywood (1988) states that the mixture is not uniform between the cylinders in a typical spark ignition engine. This fuel-air mixture contains atomized, vaporized and entrained droplets of fuel (Obert, 1968; Taylor, 1985; Young, 1955). Air and the gaseous and atomized fuel travels at a much higher velocity than the entrained fuel droplets and liquid film on the intake runner walls. Most of the authors agree that vaporization of the fuel is achieved by heat transfer from the intake tract to the finely atomized fuel. Atomization of the fuel is obtained by spraying the liquid fuel into the air stream through the jet of the carburetor (Lichty, 1967). It is therefore reasonable to deduce that the cylinder is presented with a wide array of fuel states. However, according to the literature, the entrained droplets are the greatest hindrance to the combustion process.

In any motor sport the speed of the vehicle is a function of the engine speed, gear ratio and the tire size. To increase speed it is necessary to increase any of these three components. The most common method of performing this is to generate more engine speed due to the size limitations of the tire and gear sets. Therefore, combustion events must be completed in less time as the speed increases. This makes the fuel atomization level extremely important. Since the entrained droplets must be vaporized before being burned, precious time is lost during the combustion event to vaporize the fuel in the cylinder of the engine (Streeter & Lichty, 1933). Since the cylinders have varying amounts of liquid fuel droplets in them, this varies the engine output by cylinder and cycle. To assure that the leanest cylinder in the engine receives enough fuel to function properly, the entire mixture of the engine is overcompensated to assure that the "starved" cylinder receives the proper amount of fuel. This increases the power output of the lean cylinders more than it decreases the overly rich cylinders, resulting in a net increase in power. The optimum situation would be to have the cylinder of the engine receive a fully vaporized mixture before entering the cylinder (Lichty, 1967).

Harrow (1988) disagrees since completely vaporized fuel has a lower density than liquid fuel a cubic foot of air carries a smaller mass of fuel when completely vaporized. In his studies, Harrow discovered that a fully vaporized mixture caused a nine percent reduction in power output when compared to a standard carburetor mixture. The fully vaporized mixture did show a reduction in brake specific fuel consumption for lower air/fuel ratios, which would indicate an increase in the thermal efficiency of the engine.

In 1988, Shayler and Armstrong found that manifold assessments should include determining both the fuel and air distribution pattern. Since the airflow maldistribution is relatively small compared to the fuel flow maldistribution, it is reasonable to assume that equal air/fuel ratios should indicate equal distribution of fuel to the cylinders. However, Heywood (1988) contends that a spread of one or more points of air/fuel ratio from the richest to leanest cylinder is practical in the current carbureted engine. He also contends that the cylinder specific charge distribution varies in the air/fuel ratio in each charge. It could be deduced that this could lead to a variance in flame speed throughout the combustion process and therefore a variance in engine output. Also, the distribution of fuel to each cylinder from filling to filling can vary due to the periodic filling of the cylinders. The largest variation between cylinders occurs at wide-open throttle.

Lichty (1939) adds that using a single cylinder engine with various air/fuel ratios can indicate perfection of fuel distribution by relating power output of the multicylinder engine to the single cylinder engine. He also indicates that the most troublesome distribution problem is to have one weak cylinder while all of the rest receive uniform mixtures. This causes all but one of the cylinders to receive overly rich mixtures to ensure the lean cylinder fires appropriately and, therefore, wastes fuel as it is exhausted during the exhaust stroke of the engine.

At full load, it is important to utilize all of the air available to obtain maximum power (Heywood, 1988; Streeter & Lichty, 1933). To ensure that all of the air that the engine ingests is consumed a richer than stoichiometric mixture must be used. The stoichiometric ratio of 14.7:1 is the ideal ratio of air to fuel for the complete release of chemical energy (Bohacz, 2000a). Increasing the mixture further can also increase power through cooling the mixture and increasing the induced air density. To induce the largest amount of air possible at high power outputs and high rotational speeds, a large manifold cross section is necessary (Streeter & Lichty, 1933). This type manifold tends to negatively affect low-end power formation due to the decrease in flow velocity at low engine speeds and the inherent loss of entrained particles due to gravitational settling.

Intake Manifold Design

After reviewing the literature, it has been shown that the design of the intake manifold is crucial to the proper operation of the internal combustion engine, especially at high loads and operating speeds such as experienced in drag racing. The intake manifold of the carbureted engine is subject to many design constraints which all require compromise (Shayler & Armstrong, 1988). Heywood (1988) lists the following as important design criteria: good distribution of the air and fuel to the cylinders, low resistance to flow, good heating of the fuel to ensure sufficient vaporization, and branches and runners that take advantage of ram and tuning effects of the air flow. Airflow in the intake manifold tends to reverberate due to the opening and closing of the intake valve. If the length of the intake runner is designed to accommodate these effects at certain rotational speeds such that the reverberation reaches the intake valve at the moment of opening the intake is said to be ram tuned as the fuel air mixture is forced into the cylinder by the momentum of the flow. Shayler and Armstrong (1988) add that these constraints are severe for carbureted engines as opposed to fuel injection, as the carburetor must be mounted directly on top of the intake manifold in a horizontal manner.

Since the manifold is carrying liquid fuel, it is hard to make performance predictions of how the manifold will function because of the two-phase nature of the mixture (Shayler & Armstrong, 1988). One good measure of manifold design is to test the manifold distribution under unheated conditions. This will help to determine any design deficiencies in the manifold. Small changes in manifold design can make dramatic changes in how the fuel-air mixture is distributed by the manifold. However, not all changes that are beneficial in one operating regime will benefit all regimes, i.e. transient versus steady state. Performance of the engine at part throttle operation can require increased provisions for the preparation of the mixture (Leydorf, Minty & Fingeroot, 1995). Such provisions could include raised ribs in the heated portion of the riser floor, sharp edges at the bottom of the riser, and increased velocities in the manifold. Some of these provisions could hurt wide-open-throttle performance.

With regard to manifold size, it depends upon the specific use for which the manifold is designed. Small manifolds tend to increase the power output of the engine at low speeds due to the increase in flow velocity (Lichty, 1939). This tends to negatively affect the power output at higher speeds due to the throttling effect of the small runner areas. If one hopes to achieve maximum power at higher engine speeds, a large cross section manifold is required to decrease the flow restriction. This also holds true for the ports in the cylinder head and the valve area, as the major restriction in the system can be in any of its parts and would be the component with the smallest cross section (Streeter & Lichty, 1933). In a sport such as drag racing where high rotational speeds of the engine are developed and part throttle operation of the engine is at a minimum it is desirous to have a large single plane intake. This provides the smallest amount of pumping loss in the intake system of the engine and leads to higher peak horsepower at a higher rotational speed. However, when accelerating from low speed, such as the beginning of the race, a large accelerating charge of fuel is required from the accelerator pump portion of the carburetor to offset the fuel that is lost from the air-stream due to the low velocities (Lichty, 1939).

The optimum shape of the runner in the manifold would be of circular cross section as this offers the least resistance to flow (Lichty & Streeter, 1933; Lichty, 1939). This shape of the manifold runner would be the most desirable if the manifold only had to transport air or gas but since liquid is involved a rectangular cross section is used. One of the downfalls of the circular cross section is that it provides a channel for the liquid fuel to flow in. By having the liquid fuel on the floor of a rectangular cross section manifold there is a much larger area for the fuel to be exposed to evaporation from the heating of the manifold and reentrainment by the flowing air. Also, unevenness of the floor should be avoided as this creates areas for the liquid fuel to puddle and cease to flow toward any one of the cylinders.

Smooth manifold walls do not help the mixture breakup and form smaller droplets (Smith, 1968). In addition, when the throttle is quickly opened, the sudden rise in inlet pressure to near atmospheric pressure causes the fuel that enters the tract to adhere to the walls of the runner rather than atomize and vaporize. Smith adds that what might be considered flow restrictions, surface imperfections in the manifold runner, help to increase turbulence and therefore the mixture quality. Thus, the practice of polishing the walls of the intake manifold runners, using a die grinder with carbide burs and sanding rolls, to achieve a smoother surface is actually inhibiting the formation of properly mixed fuel and air. Streeter and Lichty (1939) disagree with Smith's approach. They tend to believe that a rough surface leads to growth of the wall film from the increased resistance to flow. Their recommendation is to have a smooth wall in the intake manifold runner, as it tends to reduce this tendency.

Conclusions

Maximum power output is achieved by having a uniform mixture distributed evenly among all of the cylinders of the engine. This is achieved through the proper design of the intake system. This is critical in a sport where hundredths of a second determine the winner of the race. As a vehicle makes more power it is able to more rapidly accelerate the rotating mass of the drive train to a higher rotational speed. The speed of a vehicle is a function of the rotational speed of the engine, the gear set used in the drive train and the diameter of the tire used on the vehicle. Therefore, with all other things being equal, the vehicle that can accelerate the rotation of the drive train the quickest will win the race.

For maximum charge density, and the proper amount of fuel evaporation, the heat input into the floor of the riser needs to be applied correctly to avoid overheating the air and fuel beyond evaporation. Rectangular runners should be used and low spots should be avoided to minimize the tendency for liquid to puddle on the floor of the manifold. Streamlining should only be used when the cross sectional area can be held constant as to reduce the likelihood of the liquid fuel droplets to precipitate out of the air stream. Using guide vanes in bends and turns reduces flow separation and can be used in conjunction with streamlining to increase volumetric efficiency.

In two-phase flow the flow of the air and vaporized fuel can be considered independent of the liquid flow but the liquid flow is definitely dependent upon the air and vaporized fuel flow. Therefore when testing manifold designs it is important to include both air and fuel in the test. Using the same reasoning it can be concluded that during testing equal air/fuel ratios between cylinders is indicative of equal fuel distribution.

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