Large Scale Model Railway Engineering

Section 4 STEAM

After a couple of months off I'm back at it again. This month I am going to start dealing with Engineering a steam locomotive. Starting with the Basics, our first subject of discussion is STEAM. This will give us a good foundation when we talk about boilers and cylinder sizes, etc.

Steam is generated by evaporated water. The point that is occurs is called the Boiling Point which is a function of the pressure exerted on water. Pure water at sea level (standard atmospheric pressure = 14.7 PSI) boils at 212 degrees F. This temperature increases as the pressure goes up and drops if the pressure decreases (vacuum conditions). Table 1 shows the boiling point at various temperatures.

There are two types of steam that is used in power applications: saturated and superheated. Saturated steam is defined as steam that is in contact with and in thermal equilibrium with the water. The temperature when this occurs is called the saturation temperature, ie 212 degrees F at standard atmospheric pressure. If either the pressure or temperature is known, the other can be determined from the tables or curves that are published in many technical hand books.

Superheated steam is defined as any steam at a temperature above its saturation temperature. To define the state of supeheated steam we usually state the pressure and the temperature. Often we speak of the degrees of superheat, which is the difference between the actual steam temperature and the saturation temperature.

Another term that is often used is the quality of the steam. The quality is the percentage of vapor in the vapor-water mixture. For example 95% quality would mean 95% vapor and 5% water by weight.

On our miniature locomotives we usually use saturated steam (no super heaters) because of the problems involved with small superheater tubes and the fact that it is difficult to get a large amount of superheat in a small boiler. The amount of work that can be performed by a steam engine depends on the amount of heat that can be released from the steam. the higher the pressure the greater this heat. With saturated steam the heat available depends entirely on the pressure, while with superheated steam there is additional heat that was added in the superheating process that can be released as useful work.

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Section 4 The Steam Locomotive

This month we are going to continue our discussion on designing a steam locomotive by determining the cylinder and drivers size required to pull a given size train.

To make things simple we will use the same parameters that we used back in section 1 when we talked about the amount of tractive effort required to move our train over the railroad. We calculated that we needed 74.5 lbs of tractive effort and we wanted a top speed of 8 miles per hour. The only other piece of information that we need to size our cylinders and wheels is the boiler pressure. We will use 125 PSI in our example which is typical for a 1 1/2 scale model.

Our first step is to pick the size of the drivers, which are usually determined by the size of the drivers on the prototype locomotive or by what is available from the live steam suppliers. One should remember that as a general rule of thumb the wheel speed should be kept below about 300 RPM. Using 300 RPM and a 8" diameter wheel we can calculate our track speed by finding the circumference of the wheel and multiplying by the RPM.

8" dia X3.1415 = 25.13" per revolution

25.13"/revolution X 300 RPM = 7539 in per minute

7539" per minute /1056in/min./MPH = 7.13 MPH

This is close to the 8 MPH that we seek, so our drivers will be 8" in diameter. The cylinder stroke is usually about a third of the driver diameter which in our case is 2.66". we will round it up to an even 3".

Now that we know the driver size, cylinder stroke, boiler pressure and the required tractive effort required we can find the cylinder bore that we should use.

Before we calculate the cylinder bore however we have to talk about the boiler pressure and cylinder pressure. First of all we have pressure drops

Table 1 shows the properties of saturated steam at the pressures we use in our locomotives. This data will be used later when we start sizing the boiler, cylinders, water pumps and other components. The first column of table 1 is the boiler pressure, the second column is the amount of heat required to generate the steam starting with 32 degree F water. The third is the volume of one pound of steam, the fourth is the steam temperature and the last column is the volume of steam generated by one cu inch of water.

Next month we will start sizing components.

boiler pressure	btu	cu ft./lb	temp F	cu in steam per cu in water
80psi	1187	4.60	325	285
90psi	1188	4.30	330	258
100psi	1189	3.88	338	237
110psi	1190	3.59	344	219
120psi	1191	3.33	350	204
130psi	1193	3.11	355	190
150psi	1195	2.75	366	169

TABLE 1

$$d^2 = \frac{\text{TRACTIVE EFFORT (LBS)}}{\text{MEP} \times \text{STROKE(FT)} / \text{Driver DIA (FT)}}$$

$$d^2 = \frac{74.5 \text{ LBS}}{101 \text{ (MEP)} \times .25 \text{ (FT)} / .687 \text{ (FT)}}$$

$$d^2 = 1.96$$

$$d = \sqrt{d^2} = 1.40 \text{ BORE}$$

In the above equation we get a bore size of 1.40" which seem a little small. Well it is because our original value for the tractive effort that we needed was in fact low for a locomotive with 8" drivers. A more realistic value would be about twice this or 150 lbs. Using this value we find that we require a bore of 1.99" which we will round up to 2.00". For the rest of our discussion we will use cylinders with 2 inch bore and 3 inch stroke with 8 inch drivers.

Next month, THE BOILER.

Section 4 The Steam Locomotive (continued)

Last time we calculated the cylinder and drive wheel size for our locomotive; the next thing we want to do is size our boiler to supply enough steam.

There is no exact formulas for determining the size of the boiler because of the many variables involved, however over the years I have found some general guidelines that if followed usually give satisfactory results. These are general guide lines and not hard and fast rules.

I. HOW MUCH STEAM

The first calculation we must make is to determine the quantity of steam needed. This can be found by multiplying the area of the cylinder times the stroke times 4 strokes per revolution. For example:

Piston Area = (2" DIA / 2) X 3.1416 = 3.14 in sq.

Stroke = 3"

Volume = 3.14 in sq. x 3" stroke x 4 strokes/ Rev =
= 37.7 In cu. / Revolution

We will use this later when we size the feed water pumps or injectors.

II GRATE AREA (fire box)

To find the grate area, one common method that I use is to take the maximum tractive effort and divide it by 3.5. From my example:

$$\text{Grate Area} = \frac{\text{150 lb T.E.}}{3.5} = 42.8 \text{ sq. in.}$$

This has worked out well on the locomotive that I have built when using coal as fuel. A slight or larger area is preferred for oil or propane fired boilers.

III NUMBER OF FLUES

I have found that the area of the flues should be approximately 1/8th the area of the fire box. For our example of 42.8 sq in. fire box area this would mean that we need a total flue area of 5.35 sq. in. Our next step is to determine the size of the flues we want to use and from this we can determine the number required. If one plans on burning coal it is important that we keep the ID of the flues big enough so they do not plug up. Usually it is recommended that they should not be smaller than 1/2 ID. On oil or gas fired boilers the flue size is not as important since there is less chance of plugging. In our example we will use a 3/4 OD X 5/8 ID tube which is common for an engine of this size.

The area of a flue tube is found by:

$$\begin{aligned} \text{Area} &= 3.1416 \times \text{rad}^2 \\ &= 3.1416 \times (.312)^2 \\ &= .305 \text{ IN} \end{aligned}$$

If we need a total area of 5.35 in and each flue tube is .305 in we should use:

$$5.35 \text{ in } / .305 \text{ in } = 17.54 \text{ tubes}$$

We will round this us to 18 flue tubes.

This is great assuming we can fit 18 tubes in our boiler. A quick layout on a piece of paper will give you the answer. One thing to remember is to allow sufficient steam space at the top of the boiler. I have found that it is often better to use fewer flue tubes and lower the crown sheet to gain space for steam and water than to squeeze in the maximum number of flues and have to have a very high crown sheet with little space for steam.

Next month we will finish our discussion on the boiler and take a look at fuels and the FRONT END (smoke box).

STACK & EXHAUST NOZZLE

Section 4 The Steam Locomotive (continued)

We will continue our discussion of the boiler by discussing the smoke box and how to properly layout the stack and exhaust nozzle.

The purpose of the smoke box is to create an area of vacuum to cause the flow of air up through the fire box and flues. This air flow aids in the combustion process of the fuel and greatly increase the heat transfer between the hot gases and the fire box and flues. The draft is created by ejecting the exhaust steam through a nozzle and up the stack, or by using steam from the boiler and an auxiliary nozzle(blower nozzle).

The first thing we will do is to design our stack and then the exhaust nozzle. Practice indicates that the smallest internal stack diameter should be approximately .06 times the great area. In our example our grate area is 42.8 sq in. , so our stack area is :

.06 X 42.8 sq in. = 2.56 sq in.

2.56 sq in. = 1.63 in diameter

So our stack should have a minimum id of 1.63" and a length of at least four diameters or 6.5" including the petticoat pipe.(see figure 1)

The exhaust nozzle is usually determined by trail and error but a good starting point is about .005 times the grate area. Therefore:

.005 x 42.8 sq in. = .214 sq in.

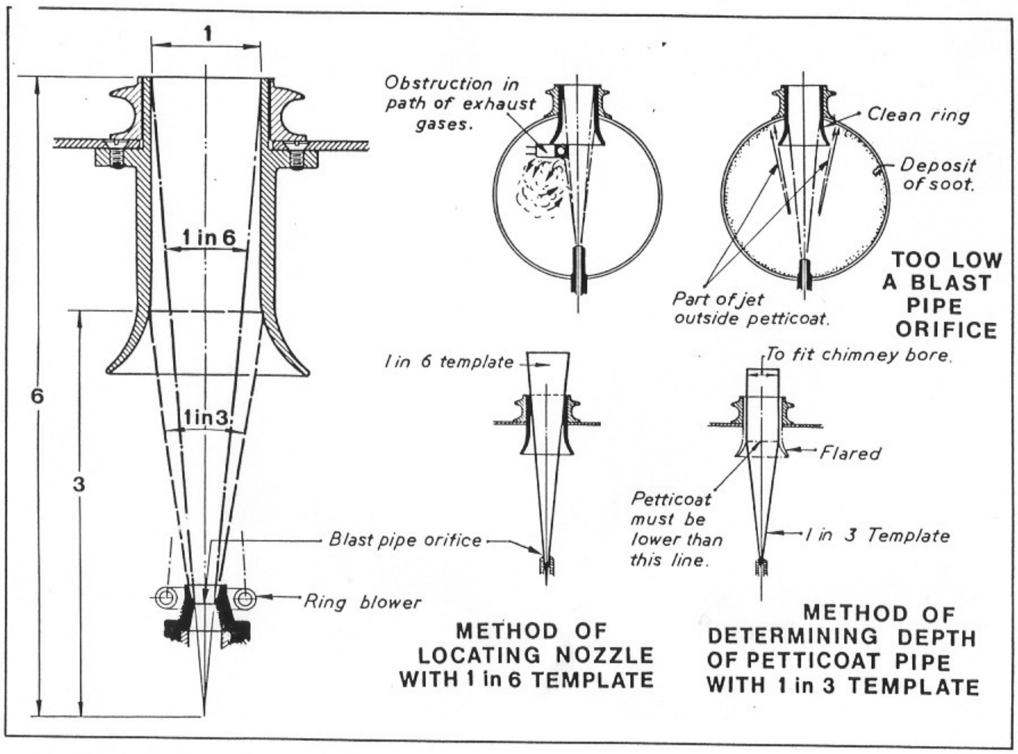
.214 sq in. = .522 in diameter

This is a good place to start but several nozzles should be tried to determine the best diameter. To small a nozzle will cause excessive back pressure on the cylinders and thus poor performance, a large diameter will reduce the draft resulting in problems keeping steam up. The nozzle shape also affect the amount of draft. The amount of exhaust blast exposed to the flue gases has a major affect on how much draft can be produced. Although a round hole is usually used as a nozzle in our small models, a star shaped or multi-ported design often gives better performance. Figure 2 shows nozzle shape that have been used over the years in full size locomotives. These shapes yields a greater surface area on the exhausting steam. This surface area causes drag on the smoke box gases which are pulled up the stack with the escaping steam thus creating a better vacuum and better draft. Fuel also has a major affect on the amount of draft needed. Much more air flow is required for solid fuel than for oil or gas and thus a smaller nozzle is usually required when burning solid fuel. The location of the nozzle with respect to the stack is also critical and will affect the efficiency of the smoke box.

The blower nozzle can be a multi-ported ring around the main nozzle or can be a single nozzle besides the main exhaust nozzle. The ring design is preferred because the jets can be directed directly up the center of the stack where as the single nozzle design be necessity must be off center so that the blower nozzle does not interfere with the main exhaust nozzle. Like the exhaust nozzle the blower nozzle is determined by trail and error to find one that generate enough vacuum for good steam generation but at the same time not be wasteful of steam.

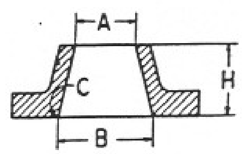
Figure 1 shows a cross-section of a smoke box showing the exhaust stand and nozzle along with the stack.

Next month we will talk about the water supply.



9 The importance of blast-pipe setting out.

Figure 1 (from Greenly's book "Model Steam Locomotives")



All Dimensions in Inches

A	*B*	*C*	*H*
1	2.4	0	1¾
1¼	2.4	0	1¾
1⅜	2.4	0	1¾
1½	2.4	0	1¾
1⅝	2.4	0	1¾
1¾	2.4	0	1¾
1.5	2.3	0.4	4½
1.6	2.3	0.4	4½
1.7	2.3	0.4	4½
1.8	2.3	0.4	4½
2.0	2.3	0.4	4½
2.2	2.3	0.4	4½
1.5	1.5	0	1¼
1.5	1.5	0	3¼
1.5	1.5	0	4½
1.5	1.5	0	6¼
1.5	1.5	0	1¾
1.5	1.7	0	1¾
1.5	2.0	0	1¾
1.5	2.4	0	1¾

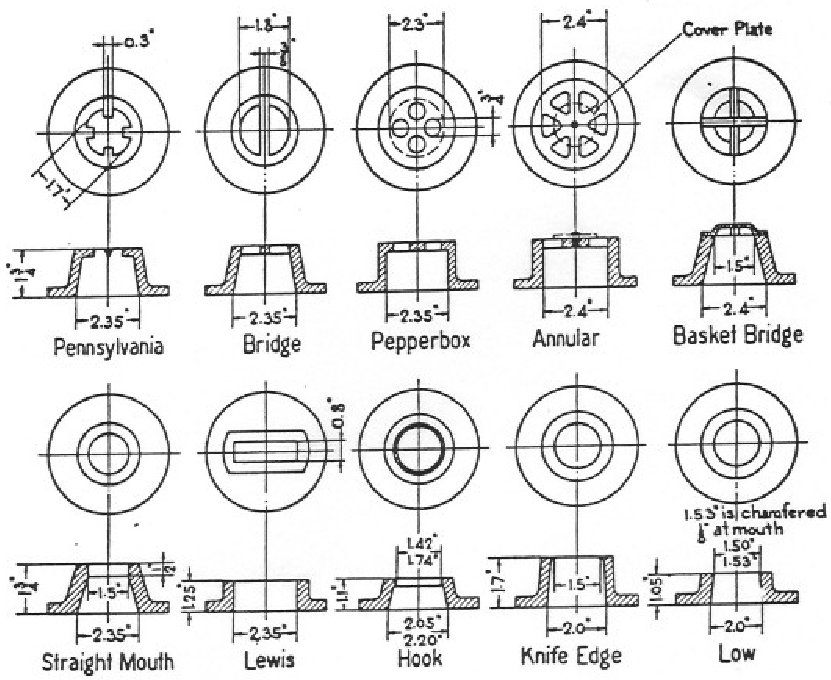


Fig. 10—Nozzles Used in University of Illinois Tests

Figure 2 "THE STEAM LOCOMOTIVE" by Ralph Johnson (Simmons-Boardman)

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DELIVERING WATER TO THE BOILER

Section 4 The Steam Locomotive (continued)

In past months we discussed the properties of steam and the sizing of some of the major components to come up with a satisfactory steam locomotive. Our next topic will cover the methods of putting water into the boiler.

There must always be at least two ways of getting water into the boiler. On full size locomotives this was usually two injectors or an injector and a feed water pump combined with a feed water heater. On our models the same thing holds true; I usually recommend three, one that works when the locomotive is moving(axle pump), one that works when standing still(injector or steam pump, and a third(hand pump) if all else fails.

Each type of feed water device has advantages and disadvantages, along with different sizing requirements. We will look at three basic types, the mechanical pump, the injector and the steam driven pump. This month we will cover the mechanical pump(hand and axle) and next month the injector and steam driven pump.

Mechanical pumps:

The first thing we must do in sizing a pump is to determine the amount of water we have to put in the boiler under typical operating conditions. Several months ago we calculated the amount of steam that is needed per revolution of the drive wheels, which for our example was 37.7 cu in.

vol = area X stroke X strokes per revolution

vol = 3.14sq in X 3" X 4

vol = 37.7 in cu

Also from our discussion of steam we know that at 120 PSI, 1 in cu of water generates 204 in cu of steam. (table 1 section 4) Therefore we can calculate the amount of water required per revolution of the wheels by dividing 37.7 in cu by 204 in cu which gives us .185 in cu.

37.5 in cu / 204 in cu = .185 in cu

This assumes 100% efficiency and no leaks, I usually figure an extra 25% to make up for this.

.185 in cu X 125% = .23 in cu per revolution

We can now use this value to size our pump. We can find the displacement of a pump by multiplying the area of the piston by its stroke. We have to be careful however to select a piston size that is not overly big or a stroke that is too long. As the piston diameter increases it takes more force to push the water into the boiler against the boiler pressure , causing an uneven load on the locomotive which results in the locomotive lunging on each stroke. The best way around this problem is to use a pump with two cylinders with the the pistons 180 degrees out of phase so that one piston is on the pressure stroke while the other is on the suction stroke. A double acting pump where the piston pumps in both directions also helps.

Sizing the pump is a bit of trail and error. Lets try a single acting pump with a piston diameter of 1/2 inch, a stroke of 5/8 inch and 2 cylinders. The area of a 1/2 inch piston is .196 in sq and with a stroke of 5/8 inch gives us a volume of .122 in cu per piston and since we have two pistons in our pump our total output is .244 in cu per revolution of the drive wheels. We calculated that we needed about .23 in cu to keep up with our steam requirements, so this would be an acceptable design. In general I have found that a 3/4 dia piston is about as big of a piston as should be used on a 1 1/2 scale locomotive.

The output of a hand pump can be found using the same method as was used for an axle pump. Again keep in mind that a large diameter piston makes for hard work on the part of the operator. A 1" diameter is about as large as one wants to go and still maintain a reasonable pumping effort; at 120 PSI it takes about 100 lbs of force on the piston to force water into the boiler and even with a 5 to 1 mechanical advantage on the pump handle it would take 20 pounds of force on the handle.

Next month we will continue with the injector and steam pump.

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Section 4 The Steam Locomotive (continued)

This months topic concerns the design and installation of injectors. The main advantages of using an injector for putting water into the boiler is that they operate equally well while the locomotive is stationary or moving, and is more efficient than mechanical pumps, as there is no moving parts. The drawback is their reliability to always work when needed.

An injector works by converting the pressure energy of the steam into kinetic energy, imparting this energy to the feed water and finally converting the kenitic energy back to a pressure higher than the boiler pressure. This is accomplished by a series of tapered cones. When an unbroken flow of fluid is moving through a closed chamber, its velocity and pressure are interchanageble as the cross section area changes.

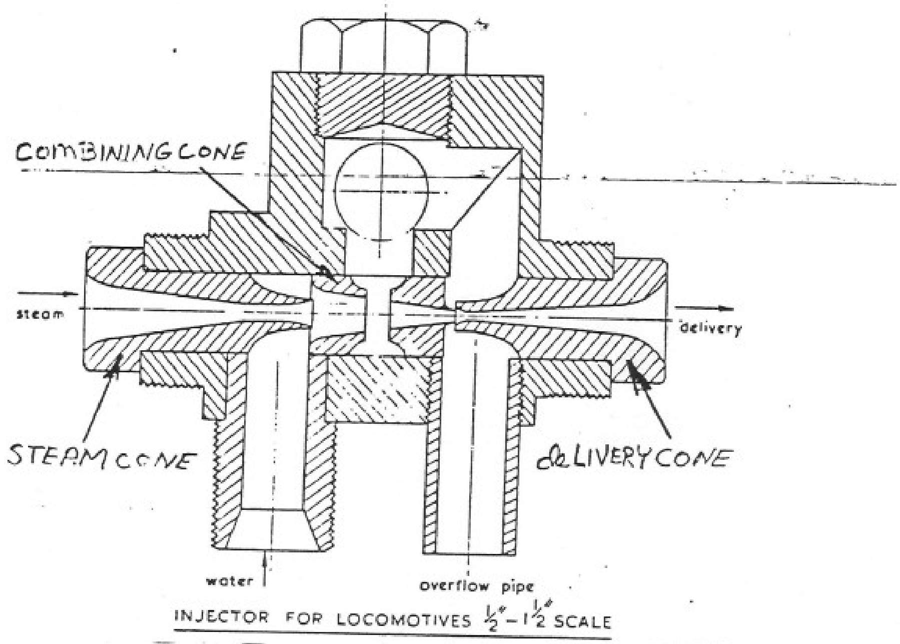

Figure 1

Figure 1 shows a typical injector as used in model locomotives. It consists of the steam cone, the combining cone and the delivery cone, each being mounted in line inside the injector body. Steam from the boiler is admitted to the steam cone while feed water is admitted between the steam and combining cones. The steam cone function is to convert as much of the pressure energy into kenetic energy. This is done by admitting steam into a cone which first converges to speed up the flow of steam and then diverges, so that the steam is expanded until its pressure is lower than atmospheric. The combining cone allows the feed water to mix with the steam again forming a high velocity flow at the end of the cone. The delivery cone then takes this high velocity low pressure flow and convert it to a lower velocity higher pressure flow, in fact convert it to a pressure higher than the boiler pressure thus allowing the water to enter the boiler. In the process the feed water is heated due to its contact and condensing of the steam.

The output of a small injector of this type can be found by dividing the delivery cones throat (smallest diameter) X 1000 squared and deviding by 40.

delivery (ounces/minute) = dia X 1000 / 40

For a delivery cone with a diameter of .060 one could expect a flow of approximately 90 oz per minute or .66 gal/min.

As one can see from above we are looking at some very small cone dimensions and that it does not take a very large piece of dirt or scale to plug up a cone and make the injector useless. This is why their reliability is not always as good as one would like. However well made the injector, the plumbing and valves are also important. It is best to mount it below the water level of the tender with the steam and delivery lines of ample size and with a minimum of sharp bends to minimize the pressure drops. Another common problem is that the injector and the feed water must not be hot or it just won't work. A leaky boiler feed check valve will prevent an injector from working.

Another factor that turns off many people is that an injector is a very precise device and is difficult to make and thus relatively expensive. Not only are the cones very small but their alignment and surface finish is very critical if they are to work.

Several books like L.B.S.C. SHOP SHED AND ROAD and Martin Evans book THE MODEL STEAM LOCOMOTIVE goes into great detail on how to build one and how to size the various cones for those who are adventitious enough to try.

Next month the steam driven water pump.