Ken's “simple” guide to designing gas burners for model boilers.

Premis:

After many years of making the gas burners that I needed for model steam boilers – including modifying other burners for Butane “camping” gas – I realised that I needed some straightforward rules to design burners of any “new” sizes, where I had little clue as to sizes of the various parts. Ealier work was very much “empirical” in that I would make something, then modify it bit by bit until I reached a satisfactory solution. But the “Engineering way” is to do a design, then make it and do any final tweaking or fine tuning for the unique application conditions (e.g. back-pressure in the firebox of a boiler, cooling effects from the boiler that quench the CO combustion, Etc.).

So I researched the web and found almost nothing to help!

Source information:

Some information is available in the K.N.Harris book on building boilers. - This enables an engineer to decide the size of burner required (as a minimum). I'll call this phase 1.
An Engineering paper (Dept. of Mech. Eng., Queen Mary's university, London) – published on the web – gave detailed maths to determine gas pressure, air entrainment, etc. - but within the text there are some simple “rules” that seem to work well = I'll call this phase 2.
Some of these rules are in my memory – without being tracable – as I have read and picked-up odd comments from my history of looking at this subject, but not studied in depth. Some is from my engineering history and training.
There is also a little information in Tubal Cain's Model Engineers Handbook, and I found a table by Pyronics System on gas “power” versus jet size to be useful. There are other snippets in odd papers. e.g. https://nvlpubs.nist.gov/nistpubs/nbstechnologic/nbstechnologicpaperT193.pdf

Phase 1: How much Gas?

This may be an odd question, but is the core of the subject.

First it is necessary to determine how much “heat” is required – and the heat comes from burning gas and air – which are directly related. – a summary here:

We are dealing in “Power” - I.E. the rate at which we can convert energy from one form to another: as in How much work is the engine doing (continouusly)? - so how much steam do we need? - and how much heat does the boiler need to boil the water and develop the steam? And *how much gas do we need* to burn to generate the heat?

K.N.Harris adequately covers the first part of “how much steam do we need? Simple steps:

1. Bore and stroke and rpm of the engine to determine a Volume per second of steam required.
2. Pressure (working pressure of boiler, or pressure required to develop the torque needed to start the engine under load – e.g. a loaded locomotive pulling away from rest).

   He shows an example that determines a need for 1570 cu.in of steam at 75psi.
3. From Pressure and volume requirements, K.N. Harris determines the “required Heating area” of a boiler – and depending on the type of boiler gives some standards for how much steam ***per heated surface area*** can be developed in the boiler.

4. Typically, depending on the type of boiler, K.N.Harris uses a “steaming rate” of **2cu.in/min.** of water per 100 sq.in of heating surface. - using his table I to convert from the steam required at NWP to the water needed. (It may be sensible to design a burner to achieve the requirements for 3cu.in./min to be sure it is adequate for the maximum the boiler can take. You can turn-down the gas a bit, but can't easily increase the rating of a burner once made!). One can only guess at the boiler application to determine the maximum steaming rate, until the engine is fully loaded and sensible measurements taken.
5. So having developed the amount of heating surface we have, and the related quantity of steam we can develop, based on the quatity of water we must boil we can convert this into the energy we need - PER SECOND.
    1. First factor: For steam at 100psi, we need 1152BTU to boil and heat 1lb. of water. (1lb. = 453.6gms.): So we need 2.54BTU to generate steam at 100psi from 1gm of water.
    2. Also: 1cu.in. of water = 16.38ccs., which is also 16.38gms. of water. (S.G. = 1).
    3. 34121BTU/hour is 1kW. and 1BTU = 1055J
6. From this we can deduce that at 100psi we need 2.54BTU /sec = 1055 x 2.54 = 2680W. to continuously supply the steam. (Compare this to a 2kW. Kettle, and it does seem reasonable.). This is based on K.N.Harris's values which in turn have considered the inefficiencies (losses) within the heat exchange in the boiler. They are also very generalised figures, so a bit of specific knowledge can refine the estimates.
7. But this does not include the losses of heat we must generate (by burning gas) to let the Hot gas go out of the flue. (I cannot judge losses from the exterior of the boiler as these vary too greatly depending on the lagging – or none!). I therefore assume we need 10% more heat so add a factor of 1.1 to my calculations of the heat we require from the input gas. Therefore I think it reasonable to use the following constants:
    1. For steam at 100psi, we need GAS to give us 1267BTU to boil and heat 1lb. of water. (1lb. = 453.6gms.): So we need **2.79BTU** to generate **steam at 100psi** from **1gm (1cc.) of water.**
    2. 1cu.in. of water = 16.38ccs., which is also 16.38gms. of water. =>Therefore we need <u>**GAS** for **45.76BTU** to generate **steam at 100psi** from **1cu.in of water.**</u>

So, in summary: we have a factior to convert the amount of water we must boil and further heat into the gas requirement in BTU.

e.g. for a 4” dia. vertical boiler with flue tubes of heating area 120sq.in. at 100psi NWP:

At 2cu.in water/min. /100sq.in heating surface: we need gas to generate steam at 100 psi from 2.4cu.in/min. of water:

I.E. 2.4cu.in/min. => 2.4 x 60 = 144cu.in/hr. => 144 x 45.76 = 6589BTU/hr.

Now: I then use the PYRONICS tables to determine a suitable size of gas jet for the fuel and pressure selected.

I have Propane at 20psi: ***From the tables***, for a “no 73 drill” jet = 28544BTU/hr.

This drill is 0.024” dia: => area = 0.00181sq.in. By pro-rata of the area of the jet we can estimate the size of jet we need for 6589BTU/hr.

We need at least: 6589BTU/hr. => therefore need a jet with CSA > 0.00181 x 6589/28544 = 0.0004178sq.in. - This equates to a jet of diameter: 0.0115”, = 0.293mm.

Therefore we can use a 0.3mm = No.8 jet:

This jet can supply JUST enough gas for our needs, but as there are unknowns (losses) such as heat lost withing the firebox that isn't into steam, heat losses from the boiler (depends greatly upon the insulation (Lagging), heat required for any steam dryer or superheater, feed-water heating, etc., then I would select the next larger jet for designing the burner.

So in this example, I shall select a 0.35mm (No.12) jet for Propane at 20psi to deliver ~9000BTU/hr. This apparent 30% increase of jet size allows the burner to supply excess heat to allow for the "unknown" losses from the boiler sides, firebox, etc.

Incidentally, for Butane there is 1.25 x the heat of Propane for the SAME jet and pressure (due to chemistry). I.E. to convert from a Propane jet to use Butane *at the same pressure* you need 0.8 of the jet AREA. So I have used the "as calculated" Propane jet size with Butane without any real problems, as this is effectively a 25% increase of gas, which means the burners have been adequate to develop the steam I needed and cope with Boiler losses, etc.

Caution when using Butane: Butane is supplied directly to burners from various containers and temperatures, so individual application pressures need to be known before an accurate Butane jet size can be determined. If using a "large" re-fillable cylinder, with a regulator in warm enough conditions that the cylinder pressure is adequate, then the jet size calculated for Butane will be correct. But even with a 2 kg. Butane cylinder, I have suffered pressure drop to only 10psi when the temperature is cool (10ºC or below) in April. And when sub-zero temperatures abound, the pressure drops to nothing! So do remember that Butane is problematic in Winter months, and will make a mockery of sensibly-designed burners.

Phase 2: Burner Design parameters from a known jet size.

The combustion of gas needs to be from at least a Stoichiometric mixture ratio, erring on the lean side (excess air). I.E. Air : Gas of 14 : 1. But this is difficult to translate into gas jet and air intake sizes: So I have comiled rules from various sources, and conclude the following:

1. Jet CSA to Mixing tube CSA – 1 : 250 (or greater). - I.E. The mixing tube shall be "the next practical size UP" from being 250 times the CSA of the jet.
2. Air inlet hole to mixing tube CSA – 1.2 : 1
3. The length of the Mixing tube shall be at least 7.5 x the diameter of the mixing tube, measured from jet. Actually, there is no harm making it a bit longer to that length measured from the end of the air-inlet hole(s).
4. AFTER the mixing tube, the mixture shall be expanded into a further volume and released through diffuser holes. The CSA of the diffuser holes shall be at least 4 x the CSA of the mixing tube.
5. After the diffuser, the mixed gas shall enter the final chamber for supply to the burner holes: The CSA of the burner holes shall be at least the same CSA, but up to 4 x the CSA, of the Diffuser holes.
6. The combusted gas shall pass into flue holes of CSA at least 3 x the CSA of the Burner holes.
7. Where a Smoke box is fitted and a subsequent Chimney or flue, the CSA of this Chimney shall be at least 2 x CSA of the flue tubes.

E.G.

1. Mixing tube internal diameter: For a No.12 jet (0.35mm dia.). CSA = 0.0962sq.mm.

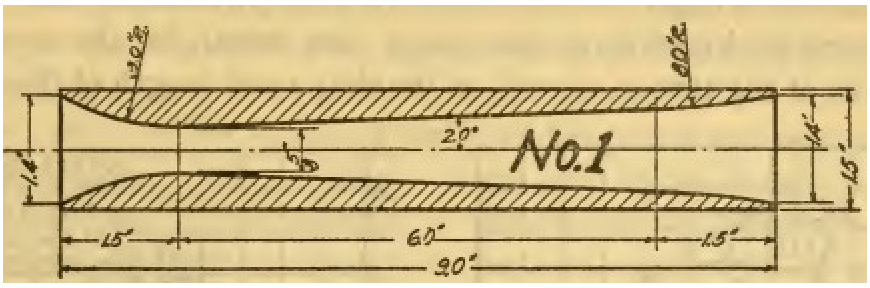
   Mixing tube CSA > 250 x 0.0962sq.mm. = 24sq.mm: => >5.53mm dia: => select a 6mm bore tube:

   BUT my experience has had 6mm dia mixture tubes "choking" with too much gas, so I use 1 size larger = 8mm I.D. Tube. I suspect this may be due to back-pressure later in the burners, and have added a table for my preferred mixer tube diameters (see below).

2. Air-hole sizing = 1.2 x Mixture tube diameter: 6mm Mixture tube => 1 x 7.2mm dia hole: or 2 holes dia. 5.1mm. For an 8 mm ID tube: use 2 x 5.7mm holes, or 3 x 4.6mm dia holes.
3. Mixing tube length – for 6mm ID tube: at least 45mm from jet to end of mixing tube; for 8mm ID mixing tube – at least 60mm from jet to end of mixing tube. It is recommended to have a minimum of 7 x diameters length of mixer tube before the gas is passed to the diffuser zone. Less than 7 diameters may mean a shortage of entrained air, poor mixing or other problems that cannot be resolved without extending the mixer tube length.
4. Diffuser region: It is often convenient to simply extend the mixing tube into the burner so the extra length is drilled as a diffuser. Or the mixture tube can end at the joint to the burner body if there is a separate diffuser chamber. (e.g. diffuser is a perforated plate within the burner): Diffuser hole CSA = 4 x Mixture tube CSA: Suppose for simplicity, for a 6mm ID mixture tube, the mixture tube continues for 100mm into the body of the burner and has a blanked end. There could be many holes in the diffuser tube as long as there is a total CSA >113sq.mm. - being 4 x CSA of the 6mm. ID mixture tube. Obviously the configuration of the Diffuser is appropriate to the shape and size of the burner, and this is where many manufacturers differ in their products, using their own (sometimes unique) technology for the diffuser hole pattern.

   Alternative styles of diffuser chanber: It is possible to use solid metal baffles after the mixing tube, or "wire wool" or mesh that will reduce the velocity of the gas and cause it to change direction to better "fill" the diffuser chamber beneath the burner. However it impossible to easily predict the gas flow and pressure seen by the burner itself, and this can take some time for experimentation. The slightest change in a baffle position can increase velocity of the gas locally, thus causing a "low-pressure zone" beneath the burner where the burner will show a cooler colour, or otherwise a region where the gas is "stopping" quickly and creating a "higher-pressure zone" below the burner, and hence a hot-spot showing brighter on the ceramic surface. Diffuser design using baffles is not covered in this document, as I know of no clear rules by which this can be achieved. But that is not to say it cannot be done, as there are many designs of burner where the designer has experimented and "tweaked" the baffles to make the burner work successfully. I have done it, but it is rarely repeatable. Hence the description of the "inverse hyperbolic" diffuser tube method above.
5. Burner holes: Depending on the shape and size of the burner, the configuration, the size and number of burner holes shall be to suit the application but the total CSA must be at least as large as the total CSA of the diffuser holes, and up to 4 times the cross-sectional area of the diffuser holes. At any rate, whatever the style of diffuser, the total area of burner holes shall not be less than 4 times the cross-sectional area of the mixture tube CSA, Except in the case of "roaring" blow-lamp style burners, where secondary air entrainment changes the rules. It is also necessary to keep these holes small in width to minimise risk of flash-back, but as this is a subject of back pressure, heat conduction away from the burner face, and other factors, I cannot prescribe rules for the actual burner hole size and spacing. (Compare a Bunsen Burner with a ceramic burner: The Bunsen burner relies upon the gas/air mixture pressure and cooling of the Bunsen tube to prevent flashback: ceramic burners rely upon the small size of holes and the designed shape of the combustion face to keep combusting gas away from the burner holes to prevent flashback – despite the "intense" heat on the surface of the ceramic).

Phase 3 – Addition of a Venturi to increase the air entrainment into the mixing tube:



Many commercial burners have followed this practice, - since the early 20th c. The principle is to accelerate the air-gas mixture – just after the air-intake – to maximise the use of the gas momentum to develop a low pressure region and thus improve the "suction" of air into the burner.

1. N.B. I have seen this shape mimicked in a central heating boiler of Cast iron, and other cast iron burners, but it is not universal, and may change the ratios determined for Phase 2: I have yet to experiment and confirm this theory. - I expect it to be very effective for low pressure gas feed but as the calculations for phase 2 above are designed to fill the mixture tube completely, thus maximising the air-gas mixture that passes into the diffuser, there may be a need to increase diffuser CSA and Burner CSA in consequence.
2. But BEWARE! - an incorrectly balanced burner design is less effective than when all details are balanced to their maximum, but the use of venturis is expected to provide up to 50% increase of air entrainment – which means an intake that is undersized can be more closely balanced to the jet size, or possibly a larger jet can be utilised? The paper suggests the venturi "injector" has been adopted to overcome designs where there is an air-intake hole of less CSA than the mixer tube, or for use with very low pressure gas injection – of down to 2in. WG. (0.072psi).
3. The Calculations in Phase 2 are currently ONLY for maximising the preformance ***without*** use of an Injector venturi.

From the US Dept of Commerce paper: based on the use of "domestic" low pressure gases available in 1920~21, they have produced an "Optimum design as described below:

I have summarised their dimensions in terms of the mixture tube diameter "D" and mixture tube CSA, "A1".

4. Mixture tube (from Tech paper 193) 1 1/2" = "D"
5. Approach taper optimum 10°, but with curved shape approx. R = 1.5~2D.
6. Length of approach taper = D. - Optimum distance of venturi from jet = 1.5D.
7. Venturi diameter: (Based on Optimum 43% of Mixture tube CSA): 0.66D (I.E. 2/3rds of the mixer tube diameter at the air intake and at the nominal exit.
8. Expansion tube taper: 2°
9. Expansion tube length: 4 x D
10. Large radius to smooth end of tapered section into Mixture tube diameter. ~>5D.
11. This "Injector" can be inserted into a straight mixer tube and locked with a grub screw – or otherwise.
12. A poorly designed injector will deteriorate the performance of the burner, by restricting the air intake: The Phase 2 calculations are based on maximising the burner performance

"without" an injector.

Conclusion:

The rules above enable a correctly sized burner to be designed for Model steam boilers.

The structure and shape of the burner will be to suit the application and user needs, but this explanation defines parameters to enable correct gas and air mixing and subsequent pressure phases within a gas burner so that good combustion takes place at and beyond the burner face.

The intent is that by proper design before any metal is cut, the maker can make "once" – and need waste relatively little time on fine tuning. There are many people who make things and "empirically tune" their way to a solution after many phases of manufacture – usually no less successful than a correctly designed part – but that process does lead to some "weird" designs (Those that cannot easily be replicated), and seldom achieves the best performance available without breaking

some rule – such as "clean combustion". However, some "technological breakthroughs" have occurred from the free-thinking approach so this is not disparraged, simply time-consuming. (Compared to a more direct design and manufacture of a good burner). - I aim for "right first time every time" and to this end believe that conventional design offers a useful advantage.

Refs:

K.N. Harris: Model Boilers and Boilermaking: (This is a "Bible" for the boilermaker.).

A simple method for the design of gas burner injectors: C.J. Lawn, Dept. of Mech. Engineering, Queen Mary University, London. https://www.researchgate.net/journal/0954-4062_ARCHIVE_Proceedings_of_the_Institution_of_Mechanical_Engineers_Part_C_Journal_of_Mechanical_Engineering_Science_1989-1996_vols_203-210

US Department of Commerce: Technologic Papers of the Bureau of Standards: No. 193 DESIGN OF ATMOSPHERIC GAS BURNERS: https://nvlpubs.nist.gov/nistpubs/nbstechnologic/nbstechnologicpaperT193.pdf

Figures:

Fig. 1 – The theoretical burner to define design ratios and parameters:

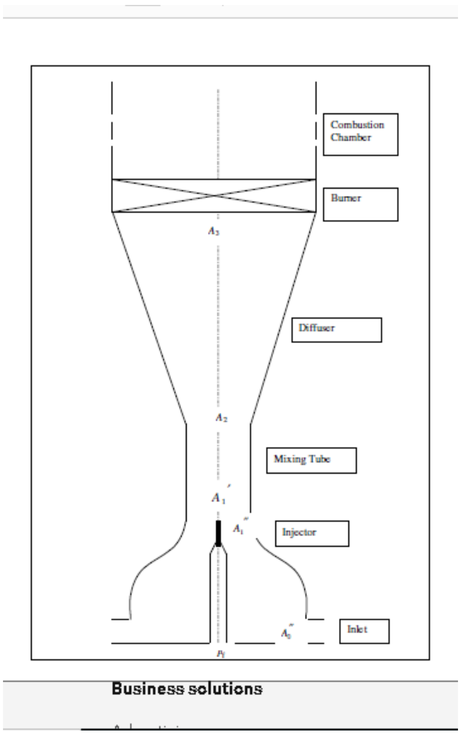


Fig 2: A bunsen burner "simple" design:

https://i.pinimg.com/600x315/15/c6/62/15c6624a9cd94bf4ad5ba11ece2f68c6.jpg

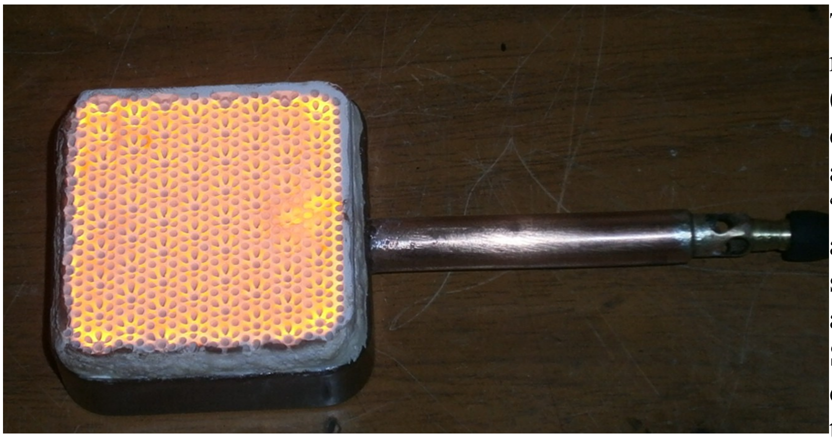
Fig 3: A "traditional" burner – with venturi – showing various features described in the text.

https://www.airheaters.info/wp-content/uploads/2011/01/upshot-gas-burner.jpg

Fig 4: – A proprietary burner with venturi and shaped air intake:

https://www.google.co.uk/url?sa=i&url=http%3A%2F%2Fgta.gastechnology.org%2Ffood_service%2FFS_BA_R&psig=AOvVaw3FVdxC-5CNCEmCzMWv7g5M&ust=1587017051972000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCNjMt7Ph6egCFQAAAAAdAAAAABAI

Fig 5: Ceramic burners following the design principles of "Phase 2" above:



This burner (2in. Square) uses a number 5 jet, 6mm mixer tube (longer than necessary – but not detrimental to function), 2 x 5mm air holes and demonstrates the "clean" combustion by having almost no excess flame above the surface of the ceramic. This is only achieved if the mixture is close to Stoichiometric, and uniformly distributed across the surface by the diffuser. Even so, with the contrast enhancement from the camera, it can be seen that there is some pressure variation within the burner causing bright spots. (e.g. at the edges where the gas flow becomes stationary, and the internal gas pressure rises accordingly).

Fig. 6: A ceramic burner in development, for a large vertical boiler.

This burner is 7 1/2" x 5" (nearly 2kW.). For a 9" diameter vertical boiler.

L.H. Photo: In order to see the variation of flame – due to internal pressure variation – the gas pressure is below the maximum (Otherwise the camera is "blinded", and detail becomes lost – see RH photo.). The variation in colour from Orange through to White is artificially enhanced by the camera. Actually, it just looks like slight changes in Orange and, "by-eye", the brightest part is only like the Left-Hand region appears in the photo.). The camera has automatic exposure and contrast. Hence the cold work-surface looks dark, but is actually a light-brown, as can be seen in the RH photo. The use of the camera and gas pressure can illustrate variations that are otherwise almost impossible to discern with the naked eye (LH Photo). But they can also mask these same images – as in the RH photo, where the shading is barely discernable. I use this information to "tune" the diffuser, as gas flow velocity within the sub-burner region affects local pressure across the burner, and I am unable to model this gas flow. - In the LH photo, it can be seen that the LH half – nearest to the inlet pipe – has a very uniform colour, therefore the pressure is near uniform. While there is a region of slightly higher pressure just to the right of centre, followed by a zone of low pressure further right (the darker shadow) which is towards the end of the diffuser. Finally, As there must be some internal velocity causing the low pressure (Shadow) region, the gas "stops" at the end of the sub-chamber, causing the higher pressure (Brighter) regions towards the corners. Some internal baffling may be needed to further tune this burner. - e.g. towards the LH edge of the shadow region to slow the gas and therefore increase the gas pressure where there is shadow, and reduce the gas pressure beyond, in the corners.

In the RH picture, there is an air-tube visible, that was used for development and was too short for adequate Mixing and Diffusion. You can see that the tube has quite a long mixing zone (no holes) but there is inadequate length to provide the required diffuser, that needs to be the full length of the burner “chamber”. Therefore a longer air-tube was being tested – based on calculations from “Phase 2” above. When finally assembled, this burner was set to run with Propane at a set pressure from a regulator, as the Butane in this test was prone to pressure drop in the cold workshop. (Pressure started at 15psi, but dropped to 12psi due to low ambient temperature. - Garage door was open for ventillation. – CO alarm does not sound when using these burners, even when the door is nearly closed to reduce draught). For Propane, I use a smaller jet and higher pressure for the same heat.

Fig 7: Here is a circular burner (mock-up) – again using a calculated design of jet and air-tube. This shows the effect of an air-tube that is too small versus and air-tube that is “one-size larger” - as required by the calculations. The picture with the “blue” flame was deliberately set-up with the same jet but a smaller inlet tube to demonstrate a fault seen on a Utube video. The only difference between these 2 “flames” is the air-tube diameter.

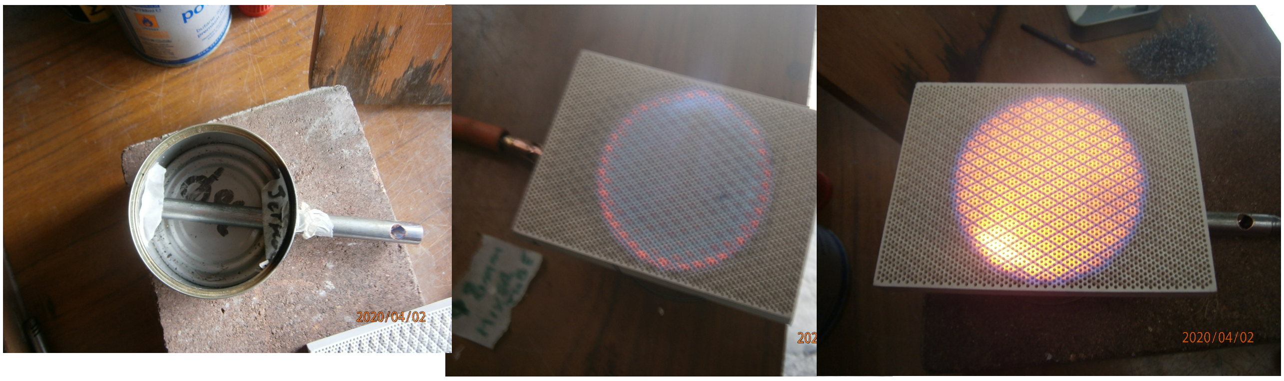


Fig 8: Here is a photo from a “proprietary” burner, showing the effect of the natural pressure increase as the gas is slowed at the end of the sub-burner chamber. The flame height is low towards the inlet (Low gas-air pressure at higher velocity) then higher at the far end of the burner (slower gas-air which creates a higher dynamic pressure). This shows a common fault that “clever” manufacturers overcome with “clever” diffuser design. You can also see that the mixture of Gas and air is poor: the “yellow” region being unburnt carbon that is burning to carbon monoxide, so the carbon particles are glowing in the heat of the flame. The RH end of this photo is where the gas-air mixture is entering the burner chamber, presumably at a velocity and poorly mixed, so the entrained air is causing the mixture to be leaner than further along the burner, and the velocity of the gas is causing the pressure to be lower – hence the flames are smaller and the correct colour. The blue cones get larger further along to the left due to increased gas-air pressure, as the velocity slows, but the mixture is “rich” (Inadequate air entrained through the air-holes/mixture tube). I would not buy this burner because of the poor design demonstrated here.

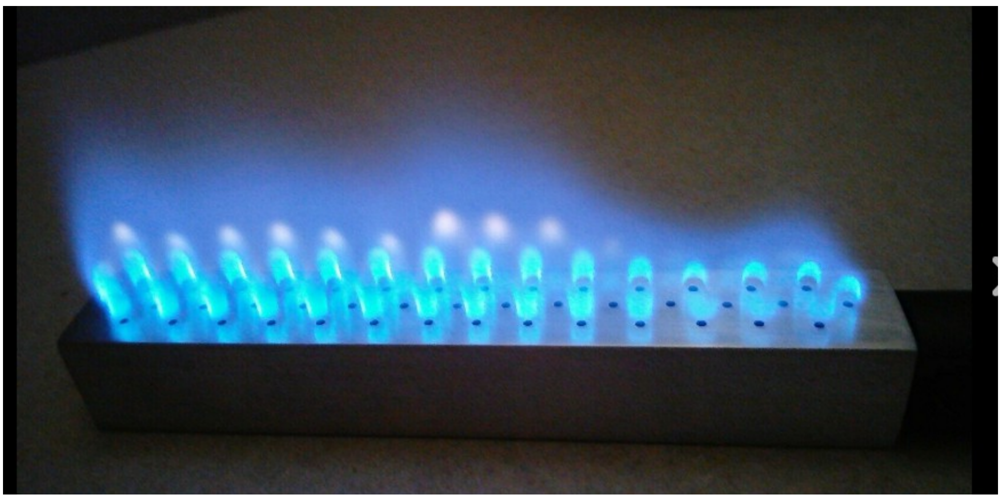


Fig 9: Extract from U.S. Paper on burner design:

Relating to the pressure in long burners, the theory explains the effect shown in Fig. 8:

7. PRESSURES IN PIPE BURNERS—FIRST AND LAST PORTS

In pipe burners all of the mixture must pass the first port. The velocity of the mixture, therefore, is greatest at this point, while at the last port the velocity is nil. At the first port there are both velocity and static pressures, but at the last port there is, of course, no velocity pressure. The static pressure is the maximum, then, at the last port. The volume of the mixture which issues from a port is dependent upon the static pressure at that port. If the ratio of the port area to the cross-sectional area of the pipe is large, there is a wide difference in static pressures and, consequently, in the volumes of the mixture which issues from the first and last ports. Table 8 contrasts the results of tests

Appendix: Tables and diagrams

Table 1: of Jet sizes and "power" (BTU/hr) from Propane.

Drill size (No.)	Drill dia. (0.001")	Area (0.001 in.^{2})	Power: (BTU/hr.) - from Propane at 20psi (or Butane @16psi)	Jet Number	Similar Jet size (mm)
			4014	3	0.2
			6272	5	0.25
80	13.5	1.82	9031	8	0.3
79	14.5	2.1	9120	12	0.35
78	16	2.56	10987	16	0.4
77	18	3.24	13905		
76	20	4	17167		
75	21	4.41	18926		
74	22.5	5.06	21727		
73	24	5.76	28544		

Table 2: KC's preferred Mixer tube sizes per jet size

Jet number	Butane (Cylinder): Mixer tube I.D. (min).	Air-holes	Mixer tube length.	Propane 20psi: Mixer tube I.D. (min).	
3	4	2 x 4mm	30mm min	6	
5	6	2 x 5mm	45mm min	8	
8	8	3 x 6mm	60mm min	10	
12	10	3 x 8mm	75mm min	13	
16	13	3x 1/2”		19	
	19			22	

3: Comments on Diffuser design: - Without the theory and maths of gas pressure and velocity!

Here is the simple way I determine how to make a combined mixer and diffuser: - Dimensions relate to Mixer ID – as determined for the jet.

Due to the conversion of gas velocity to pressure in the diffuser tube, as soon as the first diffuser hole is passed the gas stream starts to slow – and pressure build. This is an Hyperbolic function, so many small burners (without a diffuser and with a regular pattern of burner holes) show the effect of the high pressure at the last flame holes, - and small or even no gas burning at the first (due to the low pressure from a hign velocity gas stream). See Fig 8 above for the variation in flame size on a badly designed burner. This effect is also explained in the 1921 U.S. Paper. Fig 9.

To counter this, it is practical to make a diffuser with cross sectional areas of holes giving a “reverse” Hypobolic ratio from first hole to last.

I.E. If it is deemed to have – say – 4 holes for gas to escape the diffuser, then these can be given CSA = 8, 4, 2, 1 ratio of area from the first to the last, with the total CSA being >1000 x the jet CSA. (For cylinder pressure Butane).

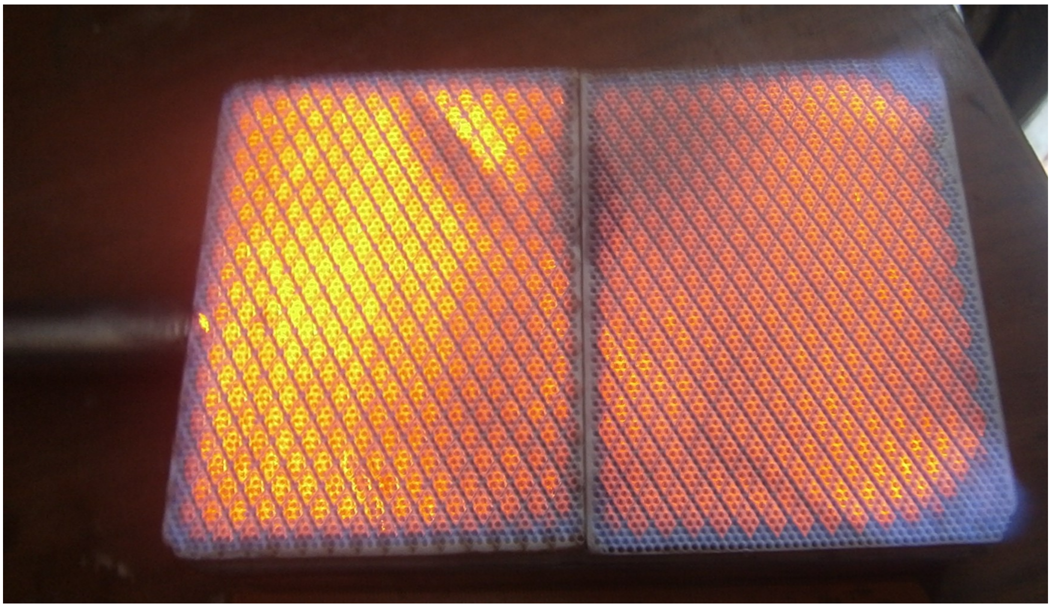
e.g. for an 8mm ID mixer tube - which would be at least 60mm long - extended 80 mm into the burner to make a diffuser tube. We can blank the end and drill side holes at 95mm, 65mm, 35mm and 5mm from the blanked end of sizes: 11.5mm, 8mm, 6mm and 4mm. Respectively. But logistically this is difficult! (the drill for an 11,5mm hole is a tad larger than the 8mm ID tube!).

So I would advocate 4 x 6mm holes from 95 position onwards, the 2 x 6mm holes from 65mm onwards, with a single 6mm hole at 35mm and a 3.5 or 4 mm hole at the position 5 mm from the end.

Depending on the shape of the burner (Square, rectanguler, circular, etc.) the amount of gas released at each point may or may not be adequate to avoid gas starvation at any point on the burner. But this “linear” design is reasonable for a “bank-card-shaped” rectangular burner. A longer narrow burner needs more holes – again of a “reverse hypobolic ratio”. A circular burner needs allowance that the gas expanding “per location” is feeding either the “narrow-ends”, or the “wider-middle” regions.

4. A cautionary tale:

I made a large Creamic burner for use beneath a 9" diameter vertical boiler, with limited flue tubes, which made it ideal for a radiant burner as it would choke with any sizable "Gas cloud" or Pan burner. (It has only 12 x 3/8" flue tubes). Thus when designed, I spent time tuning the burner (checking that the calculated jet was correct, by trying 1 size larger and 1 size smaller, as well as various gas pressures). But although my selected jet size was the optimum, on separate occaisions I had either a uniform "orange" glow on the ceramic, or a shadow region in the moddle of the burner, and it sounded like the gas was "sputtering occaisionally. I also witnessed the effect of a gas cloud moving across the surface, whereby the middle part of the burner appeared to have too little fuel to burn correctly. See below:



Also, the small flames in the far corners were "roaring" gently. A side view observed no extra flame above the surface of the burner, except at the 2 corners (RH-side of the picture).

Development: I suspected that inside the boiler, the back-pressure would reduce the velocity of the gas entrainment, and therefore make the flame more uniform across the surface, as on occaision I had witnessed a perfectly uniform colour – but could not explain why.

I therefore considered reducing the mass flow into the burner by partially blocking an air-hole (1 of 3 holes). This generated a large cloud of Blue flame above the burner, but as I carefully exposed the air-hole, the burner stabilised to a uniform orange colour. The small "blow-lamps" in the corners had also dissapeared, and I could not get them to re-appear while the burner remained lit. I tried various gas pressures in this condition, Max. to Min and back, and could not re-gain the variable pattern above – even with a fully open air hole...

However, when I turned OFF the gas, opened the air hole completely, and re-lit the burner, I regained the variable condition. Again, partially closing the hole regained the uniform combustion.

Fitting an obstruction (tape) across the half of the hole that seemed to affect the burner, meant that every time the burner was lit it performed correctly with a uniform Orange all over the surface. I do not have the boiler to confirm final combustion within the confines (and changed conditions) of the fire-box. But I estimate the the small change of back pressure will reduce the entrainment air mass sufficiently to match the effect of masking-off half of one hole ($1/6^{th}$ of the air-hole area). N.B. The part of the air-hole masked was the half closest to the jet. I have observed in many cases that the bulk of the air is drawn-in nearer to the jet than on the side of an air hole further from the jet. There are also "turbulent" effects within the Mixer-tube that are affected by such masking of an air-hole. I believe there must be some slight manufacturing variability within the air-tube that causes the effect and solution described above.

Conclusion: The gas flow within a burner is susceptable to the slightest inconsistencies, and care in manufacture is always worth the effort. But even so, final checking is always necessary, and “tuning” of a burner may be needed to alleviate any quirks.