Exhaust Tube Gas Dynamics During Puffer Circuit Breaker Operation

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Abstract: Measurements are presented of the temperature vs time in the exhaust tube of a SF_6 puffer circuit breaker during operation along with the total power dissipated in the arc, etc. These data facilitate analysis of the gas dynamics in the exhaust tube as hot gas from the arc propagates into cold gas within the exhaust tube and vice versa.

INTRODUCTION

In considering the gas dynamics in the exhaust tube of a puffer circuit breaker as hot gas which has passed through the arc propagates into cold gas in the exhaust tube or cold gas after clearing propagates into hot gas, the following issues arise

- To what degree does the hot gas from the arc mix with the cold gas in the exhaust tube?
- What determines the velocity of the hot gas propagating down the exhaust tube?
- To what degree does cold gas which enters the exhaust tube after current zero mix with the hot gas in the exhaust tube?
- What is the velocity of the cold gas which propagates down the exhaust tube after current zero, and what determines that velocity?

In the following analysis, these issues are not resolved fully; however, the issues are quantified and analyzed to a degree which, we feel, provides considerable insight.

Table 1. Interrupter Characteristics

	Type C	Type D
Exhaust tube volume from arc to Sensor 1	9200 cm^3	9200 cm^3
Exhaust tube volume from Sensor 1 to Sensor 2	7900 cm^3	10800 cm^3
Total exhaust tube volume	17100 cm^3	20000 cm^3

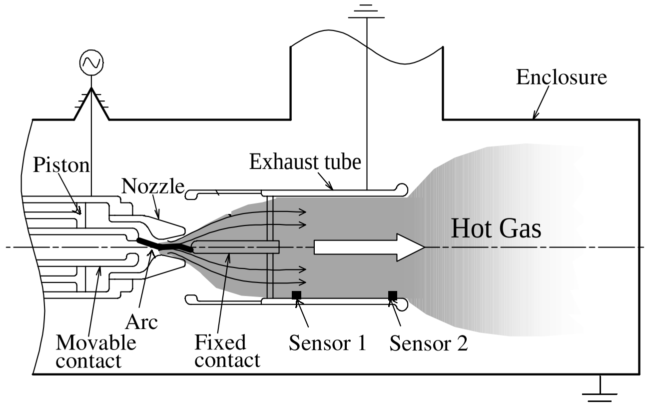

Figure 1. Schematic of model gas circuit breaker used in the experiments.

MEASURED DATA

Measurements have been made of arc power dissipation and temperature in the gas at two positions in the exhaust tube region as a function of time during interruption for arcing times of 16 ms, 18 ms, and 24 ms for two exhaust tube geometries as characterized in Table 1. The overall model circuit breaker configuration is shown in Figure 1. The gas temperature was measured using small spark gaps which protruded slightly from the wall of the exhaust tube and which had been calibrated for breakdown voltage vs gas temperature. These operated in a relaxation oscillator mode which provided a reasonably continuous measure of the gas temperature during model breaker operation. Figure 2 shows a typical data set. The temperature rises above 3000 K at both Sensor 1 and Sensor 2, the temperature at which the breakdown voltage of the sensor becomes essentially zero and above which, therefore, temperature measurement is not possible.

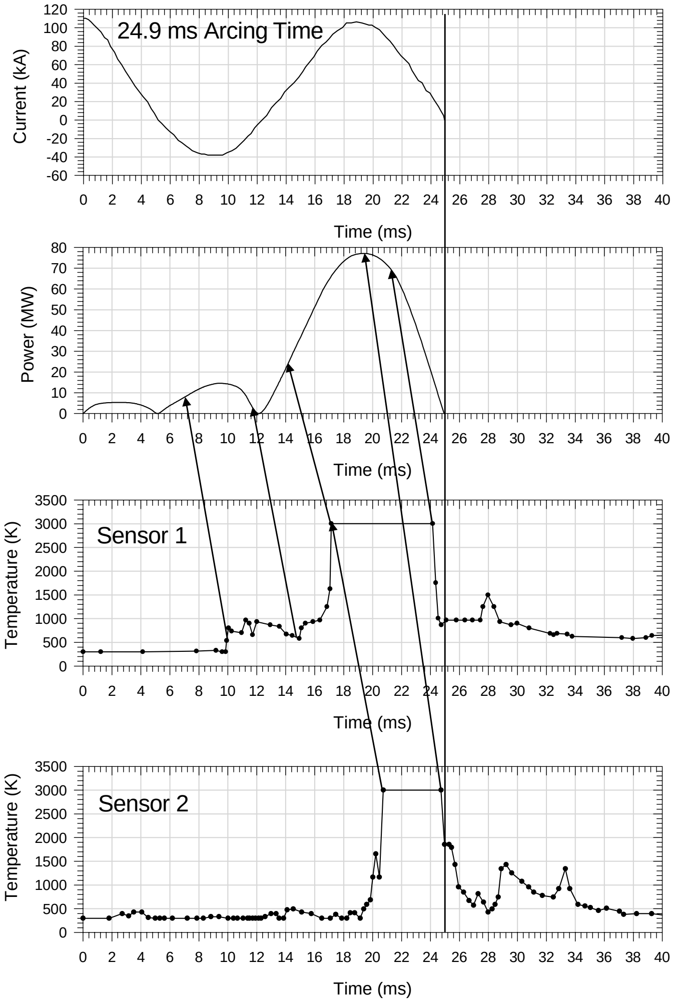

Figure 2. Data for arc current, power dissipation and temperature at two positions in the exhaust tube as a function of time during a 50 kA interruption with 50% DC offset in CB Model D with an arcing time of 24.9 ms. The arrows show the relationship between the times at which various features occur based on the measured gas velocity of about 124 m/s as hot gas from the arc propagates down the exhaust tube from Sensor 1 to Sensor 2. The use of this gas velocity makes sense in the time region where it is measured, prior to the temperature rising above 3000 K. However, use of this gas velocity as the temperature drops below 3000 K after clearing would imply that the gas which caused the temperature to drop was generated near the peak in the power dissipation, which does not make sense. Thus the effective gas velocity must change substantially around current zero.

PARAMATERIZING THE PROBLEM

As summarized in Table 1, the volume of a Type D exhaust tube is 20000 cm^3 and 17100 cm^3 for Type C. The volume from the arc to Sensor 1 is about 9200 cm^3 for both exhaust tube types. The density of SF_6 gas at room temperature and 4 bar is about 25 kg/m^3. Thus the mass of gas in the exhaust tube is about 0.5 kg for Type D and about 0.23 kg between the arc and Sensor 1. The heat capacity of the SF_6 at 1 bar is shown in Figure 3 [1]. The data from [2] at 4 bar pressure are in general agreement but much less detailed. Based on Figure 3, the energy required to heat SF_6 from room temperature to 3000 K is about 15 MJ/kg. Thus about 7.5 MJ would be required to heat all the gas in the exhaust tube from 300 to 3000 K. However as seen in Figure 4, the total arc power dissipation for Type D, 25 ms arcing time is only 680 kJ. Thus if all the arc energy went into the gas within the exhaust tube, it would be less than 10% of that required to raise the temperature of the gas in the exhaust tube to 3000 K.

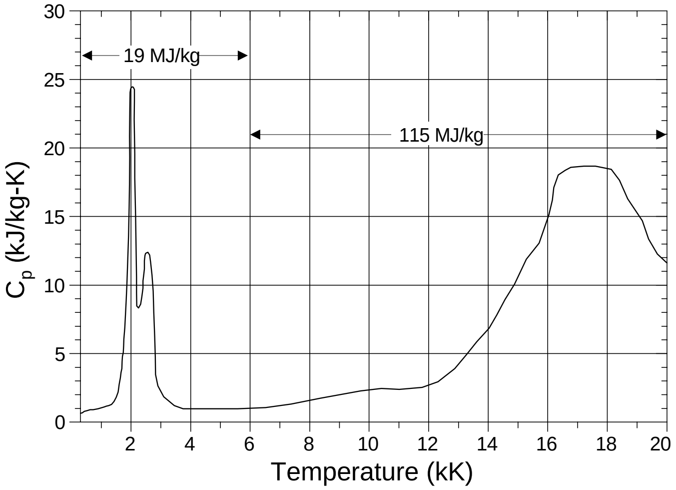

Figure 3. Heat capacity of SF_6 as a function of temperature at constant pressure from 300 K to 20,000 K. The energy required to raise the temperature from 300 to 6000 K (to form a leader) is about 19 MJ/kg as a result of the molecular decomposition from 1500 to 3000 K while the energy required to raise the temperature from 6000 K to 20,000 K (the arc core temperature) is much greater about 115 MJ/kg as a result of molecular and atomic ionization. As a result, a great deal of heat is given off as the gas recombines to atoms and then molecules which slows cooling of the gas.

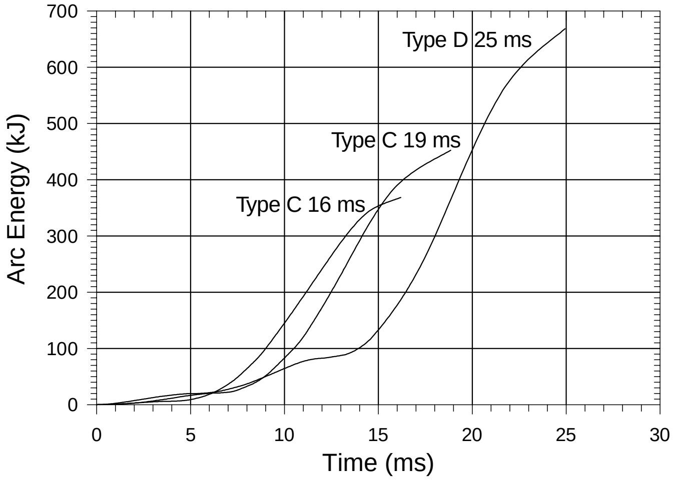

Figure 4. Arc power dissipation as a function of time.

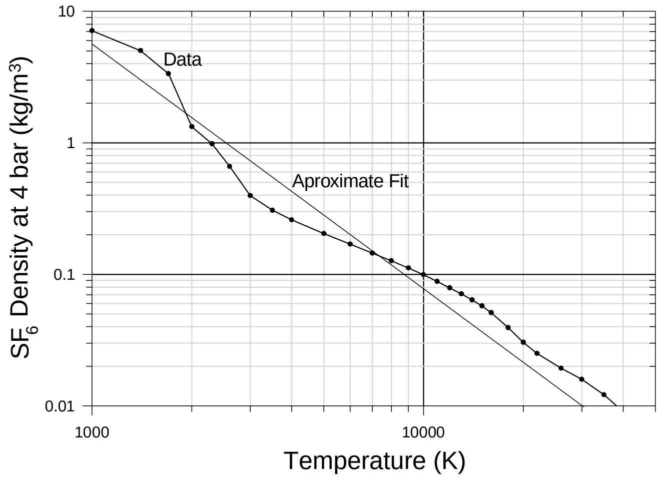

Figure 5. Data for density of SF_6 at 4 bar [2] and a rough fit there to which was used for the rough conversion of the data for mass heat capacity to volumetric heat capacity. The formula for the fit line is $D(T) = 1.607e6*T^{-1.8357}$.

However, we do not need to heat all (indeed any) of the gas in the exhaust tube to achieve a temperature of greater than 3000 K in the exhaust tube. From Figure 5, we see that the SF_6 mass density at 3000 K, 4 bar is about 0.4 kg/m^3, down by nearly two orders of magnitude from the density at 300 K of 25 kg/m^3, meaning that at a constant pressure of 4 bar the gas expands by nearly a factor of 100 between 300 K and 3000 K. Thus the energy required to heat the gas which would be in the exhaust tube at 3000 K from 300 K to 3000 K is about 120 kJ as opposed to the 7.5 MJ required to heat the gas which would be in the exhaust tube at 300 K from 300 K to 3000 K.

In other words, the arc energy is totally inadequate to heat the 300 K gas in the exhaust tube from 300 K to 3000 K. However, if the 300 K gas in the exhaust tube were replaced by 3000 K gas, then, in principle, only about 120 kJ would be required to heat the replacement gas by starting with 8 gm of gas which would require 120 kJ to heat from 300 K to 3000 K at which point it would expand from a volume of 240 cm^3 at 300 K to 20000 cm^3 at 3000 K.

Reality is between the two above extremes. Gas is heated by the arc and flows into the exhaust tube. Some of this gas mixes into the gas in the exhaust tube, and some of it displaces gas in the exhaust tube. Further analysis of the arcing test data can shed some light on these issues.

ANALYSIS OF THE ARCING DATA

Energy Balance and Implications Thereof

Data are available from three arcing tests. All the data are similar to those of Figure 2, the arrows on which show correspondence between events based on the gas propagation velocity of about 124 m/s as determined by the propagation of hot gas from Sensor 1 to Sensor 2.

Table 2: Power Dissipated Prior to Temperature Sensor Reaching 3000 K

Data Set	**Type D, 25 ms arcing time**	**Type C, 19 ms arcing time**	**Type C, 16 ms arcing time**
Sensor 1	220 kJ	220 kJ	250 kJ
Sensor 2	480 kJ	430 kJ	NA

Qualitatively, very hot gas will be ejected from the arc region into the exhaust tube. The density of the hot gas is extremely low, and the gas contracts enormously as it cools. As demonstrated above, the energy dissipated in the arc is insufficient to heat 300 K gas in the exhaust tube to the range of 3000 K. From the measured data, we can determine the power dissipated in the arc at the time that the temperature at Sensor 1 reaches 3000 K, as seen in Table 2. For the Type C, 16 ms arcing time, the temperature at Sensor 2 never reached 3000 K. The data in Table 2 suggest that about 220 kJ are required to raise the temperature of the gas between the arc and Sensor 1 to the range of 3000 K. About 20 MJ/kg are required to raise the temperature of SF_6 from 300 K to 5,000 K, an assumed temperature in the exhaust tube. Thus 220 kJ is sufficient to raise the temperature of about 10 gm of SF_6 from 300 K to 5,000 K, and above, we computed that 8 gm of gas is required to fill the exhaust tube at 3000 K. Thus the energetics imply that the cold gas in the exhaust tube is *replaced* by hot gas with very little mixing, as the energy dissipated is barely adequate to heat the gas which would fill the tube at 5000 K and is totally inadequate by over an order of magnitude to heat 300 K gas in the tube to 5000 K. In reality not all of the energy dissipated in the arc goes into the gas, but most probably does.

We can therefore formulate a picture of hot gas being injected into the end of the exhaust tube. While this hot gas has very low density, it has a rather high viscosity, about 3.6 millipoise at 10,000 K compared to 0.36 millipoise at 1000 K [2] and a rather low Reynolds number, which may account for the gas being capable of pushing the ambient, low temperature gas down of the exhaust tube with very little mixing in the process.

Propagation Velocity During Heating

The velocity with which the hot gas propagates down the exhaust tube is of great interest. The propagation velocity appears to be close to the sound velocity of the ambient temperature gas in the exhaust tube, about 125 m/s when hot gas is pushing cold gas out of the tube. At this velocity, the hot gas should be near laminar flow, while the cool gas will be in turbulent flow with a Reynolds number well over 10,000 as a result of a much greater density and smaller viscosity.

As is well known [3], gas propagating under pressure down a pipe tends to approach its velocity of sound, whether it is initially above or below that velocity. The velocity of sound in the hot gas is much greater than in the cold gas, in the range of 1000 m/s at 4 bar and 3000 K [2] vs 125 m/s at 4 bar and 300 K. Thus the hot gas attempts to accelerate toward its velocity of sound but is impeded by the velocity of sound in the cold gas which it must push out of the tube. The flow resistance increases enormously above the velocity of sound, so that the cold gas, and the hot gas which is pushing it, adopt the velocity of sound of the cold gas. Thus the near laminar flow of the hot gas, along with its relatively high viscosity, may account for its efficiency in pushing the cold gas down the exhaust tube at near its velocity of sound with very little mixing in the process.

Propagation Velocity During Cooling

If the same propagation velocity of about 124 m/s is used to correlate the time at which the temperature at Sensors 1 and 2 drops below 3000 K with the position on the current or power dissipation waveform, one concludes that the gas which caused the cooling was generated near the peak of the current or power dissipation waveforms, as demonstrated with the arrows in Figure 2. This is clearly not possible, and the only conclusion is that the gas velocity for cooling the exhaust tube is much greater than the gas velocity for heating the exhaust tube.

Once the arc extinguishes, cold gas from the arc nozzle will propagate into the hot gas in the exhaust tube. The cold gas will be turbulent as a result of its high Reynolds number, and it will be injected into a much lower density medium which can be cooled easily (as a result of its low density and volumetric heat content) and which will contract by roughly a factor of 100 in doing so. Under these conditions, the cold gas may be able to mix into and condense the hot gas at a very rapid rate. In any case, examination of the arcing data suggests that the flow velocity down the exhaust tube for the cold gas immediately after current zero is in the range of 450 to 800 m/s. The uncertainty results from the fact that the time between recovery of dielectric strength at Sensors 1 and 2 appears to be between 0.5 and 1 ms, which is too short to measure with good accuracy.

We can apply the above energy balance analysis to the situation during cooling. We can start by assuming that by the end of the arcing period, the exhaust tube is full of gas at 5,000 K. The mass of 20000 cm^3 of SF_6 at 5,000 K and 4 bar is about 4 gm. The enthalpy of SF_6 at 5,000 K is about 20 kJ/gm and that at 1000 K is very small in comparison. Thus the 4 gm of 5,000 K SF_6 can give up about 80 kJ during cooling. The energy required to raise the temperature of SF_6 from 300 K to 1000 K is about 700 J/gm. Thus the hot gas in the exhaust tube could heat about 115 gm of SF_6 from 300 K to 1000 K. If the cold gas which enters the exhaust tube ends up at 1000 K (see Figure 2), then the mass of the gas in the tube would be about 140 gm. Thus the hot gas in the exhaust tube could raise the temperature of 80% of the cold gas which enters the tube, which suggests substantial mixing as the cold gas propagates into the hot gas. The gas in the exhaust tube is at about 700 K immediately after “quenching” which suggests a similar degree of mixing.

Thus an analysis of gas motion upon clearing suggests that the cold gas enters the exhaust tube very rapidly and mixes to a substantial degree with the hot gas in the tube. This is probably the result of:

1. The high Reynolds number of the cold gas relative to the hot gas
2. The ability of the cold gas to mix with and “condense” the hot gas.
3. The large sound velocity of the hot gas relative to the cold gas.

In some sense, the propagation of the cold gas into the exhaust tube filled with hot gas must be similar to a shock tube experiment, except that the cold gas is propagating into a tenuous medium which can condense easily rather than into a near vacuum.

Activity at the Exhaust Tube Mouth

According to the above analysis, cold gas should be ejected from the exhaust tube prior to hot gas reaching Sensor 2, and hot gas should be ejected from the exhaust tube after hot gas reaches Sensor 2. A third sensor was placed outside the mouth of the exhaust tube from which we determined that the dielectric strength of Sensor 3 increases just prior to the collapse of the withstand of Sensor 2, and after the withstand of Sensor 2 drops, the withstand of Sensor 3 drops as well, all of which is consistent with the above analysis.

CONCLUSIONS

The above analysis based on energy balance considerations implies that hot gas from the arc does not mix appreciably with the cold gas in the exhaust tube but rather pushes the cold gas out of the exhaust tube to be replaced with hot gas. The propagation velocity of the hot gas down the exhaust tube appears to be determined by the velocity of sound in the cold gas being ejected from the exhaust tube.

Similar considerations imply that the cold gas injected into the exhaust tube around current zero propagates down the exhaust tube at a much greater velocity, in the range of 400 to 800 m/s which is probably related to the velocity of sound in the hot gas in the exhaust tube but also dependent on the much greater degree of mixing between hot and cold gas which occurs during cooling. However, the analysis for cooling depends to some degree on the assumed temperature of the gas in the exhaust tube at the time that cold gas is injected from the puffer chamber.

An understanding of gas flow dynamics in and just outside the exhaust tube obviously contributes to optimizing the breakdown voltage between the exhaust tube and the circuit breakdown enclosure during the transient recovery voltage shortly after clearing.

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