Steam as an extinguishing medium

1 Introduction

The intent of this document is to prove, scientifically, that 45% steam will stop the combustion in a room on fire. We will use the methods as described in *Introduction to fire dynamics*, *2nd edition* by Dougal Drysdale. This is considered one of the most important works in fire engineering.

It is not possible to perform this calculation perfectly seeing as not all the data is available. The problem is that the characteristics of smoke are not a constant. Smoke is a mixture of different components. Each of these components has characteristics but the distribution of the different components (x % A, y % B, z % C, …) is not known.

Therefore, we will make a conservative assumption. Conservative means that we will make an exaggeration. We will use a gas that has a higher heat of combustion that the components in the smoke. Methane has a heat of combustion of 50 MJ/kg. That is the highest of the hydrocarbons.

We will fill a room with the ideal mixture of methane and air. This is another conservative approach. In reality, it is extremely unlikely that the smoke will be ideally mixed with air.

2 Calculation

The ideal mixture of methane in air is 9.5%. This means there is 90.5% air left in the room. Air is composed of 21% oxygen and 79% nitrogen. This brings us to the following distribution:

CH_4:	9.5%
O_2 :	19%
N_2:	71.5%

The combustion reaction being:

$$CH_4 + 2\,O_2 + 7.52\,N_2 \rightarrow CO_2 + 2\,H_2O + 7.52\,N_2$$

The room is filled with this mixture. If we introduce 45% steam volume in the room, only 55% of this mixture remains. This leads to a new distribution:

CH_4:	5.23%
O_2 :	10.46%
N_2:	39.32%
H_2O:	45%

Let's consider a 20 m² room that has a ceiling height of 2.5 m. The volume of the room is 50 m³.

The volume distribution is the following:

CH_4: 2.61 m³
O_2 : 5.23 m³
N_2: 19.66 m³
H_2O: 22.5 m³

The combustion reaction being:

$$2.61\ CH_4 + 5.23\ O_2 + 19.66\ N_2 \rightarrow 2.61\ CO_2 + 27.73\ H_2O + 19.66\ N_2$$

It is possible to calculate the adiabatic flame temperature with the following formula:

$$T_f = T_i + \frac{\Delta H_c}{\sum n.c_p}$$

The adiabatic flame temperature is the temperature of the flame without heat losses to the environment. This is another conservative approach. In reality, the temperature will be lower due to energy losses.

The parameters are the following:

T_i: The initial temperature. Let's take 25 °C.
ΔH_c: The heat of combustion of methane. The value for this is 800 kJ/mole.
c_p: The specific heat of each of the products of the reaction. The values of the products are:

CO_2:	54.3 J/mole.K
H_2O:	41.2 J/mole.K
N_2:	32.7 J/mole.K

n: The number of moles per species.

This leads us to the following:

$$\sum n.c_p = 2.61 \times 54.3 + 27.73 \times 41.2 + 19.66 \times 32.7 = 1926.37\ J(mol.K) = 1.926\ kJ/(mol.K)$$

$$T_f = 25 + \frac{2.61 \times 800}{1.926} = 1110\ °C\ or\ 1383\ K$$

This seems to be high but Drysdale teaches us that the temperature corresponding to the lower flammability limit is to be found in a band of 1600 ± 100 K. The same value applies to the upper flammability limit. Since the adiabatic flame temperature is calculated as 1383 K we can conclude that the mixture with 45 % steam is not capable of combustion as there is no flammable range left.

3 Possible criticism

One could argue that more than 45% steam needs to be added into the room to end up with a mixture containing 45% steam. When steam is introduced, an extra volume of gasses is introduced into the room. The pressure inside will rise and this will lead that a part of the gasses is pushed out. The gasses that leave will contain partly the original mixture and partly the steam. It is correct that more than 45% steam needs to be introduced in the room to end up with the above mixture.

Let’s examine what happens when we add only 45% steam. When adding only 45% steam, we well end up with the following distribution:

CH_4: 4.75 m^3
O_2 : 9.51 m^3
N_2: 35.74 m^3
H_2O: 22.50 m^3

The total of these gasses is 145 m^3. This will lead to an overpressure and 45% of the gasses will be pushed out. When the percentages are divided by 1.45, we will end up with a mixture that fills 100% of the room:

CH_4: 3.28 m^3
O_2 : 6.56 m^3
N_2: 24.65 m^3
H_2O: 15.52 m^3

Note that there is a higher methane content and a lower water vapour content in the room compared to the first case that was evaluated.

This leads us to the following:

$$\sum n.c_p = 3.28 \times 54.3 + 22.07 \times 41.2 + 24.65 \times 32.7 = 1893\ J(mol.K) = 1.893\ kJ/(mol.K)$$

$$T_f = 25 + \frac{3.28 \times 800}{1.926} = 1410\ °C\ or\ 1683\ K$$

This adiabatic flame temperature means that, highly likely, there is a small flammable range left. It will be a small flammable range since the flame temperature is close to the LFL and the UFL.

The conclusion is that enough water needs to be applied to obtain a mixture that contains 45% steam in the volume to be 100% sure that there is no combustion possible, even not when the mixture is ideally mixed to start with.

When the mixture is not ideally mixed, there will be no flammable range left after introduction only 45% steam.

4 References

[1] *Drysdal D (1999) Introduction to fire dynamics, 2nd edition, John Wiley & Sons,*