BRANDSKYDDSLAGET

# Temperaturberäkning vid tunnelbränder

## Brandforskrapport nr 401-091

*"Temperature stratification in tunnels"*

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Internt projektnummer 103353

**2010-06-24**

# Förord

Rapporten är finansierad av Brandforsk. Arbetet är en del av Hans Nymans forskningsarbete under handledning av Haukur Ingason. Till projektet har en referensgrupp anknutits. Vi tackar följande personer, som ingår i referensgruppen, för deras insatser i referensgruppen.

| | |
|---|---|
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Rapporten är skriven på engelska med en sammanfattning på svenska.

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# Sammanfattning

Bakgrunden till rapporten är ett ökat behov av kunskap inom området bränder i tunnlar. De senaste 15 åren har ett antal större katastrofbränder i tunnlar uppstått. Samtidigt bygger vi allt fler undermarksanläggningar och tunnlar i Sverige. Kunskapsbehovet inom område är därför stort.

Syftet med analysen och rapporten är att verifiera en föreslagen korrelation för att bestämma karaktären på brandgasskiktningen via en beräknad medeltemperatur och en medelhastighet nedströms branden. Detta genomförs med data från ett antal redan genomförda modell- och fullskaleförsök. Ett sådant uttryck kan både användas för att verifiera avancerade strömningsberäkningar (CFD-beräkningar) men också för att på ett enkelt sätt beräkna temperaturer och beskriva karaktären på brandgasskiktningen vid olika brandsituationer.

Newman presenterar ett förslag på en indelning av brandgas- och temperaturskiktningen i tre olika regioner nedströms branden. Region I betecknas av en klar och tydlig skiktning, region II en blandningsregion och region III som i princip en region utan skiktning (en homogen blandning av brandgaserna över hela tunneltvärsnittet). Regionerna kan bestämmas via en korrelation som föreslogs av Newman 1982 och byggde på ett antal olika försök i en modelltunnel. Bakgrunden till försöken var en studie av placering av rökdetektor i gruvor.

I rapporten utnyttjas data från två fullskaleförsök med större bränder i tunnlar. Dessa är försöken i Memorialtunneln (USA) från 1993 och försöken i Runehamar i Norge (2003). Dessutom studeras mätdata från två modellförsök utförda i Sverige av FOA-SP (FOA är nuvarande FOI, Totalförsvarets Forskningsinstitut) och SP (Sveriges Tekniska Forskningsinstitut). Fullskaleförsöken och modellförsöken studerades utifrån den av Newman föreslagna korrelationen.

- Resultaten visar att om enbart temperaturkvoter studeras stämmer den av Newman föreslagna korrelationen bra överens med både modellförsöken och fullskaleförsöken
- När Froudetalet införs i analysen är korrelationen mellan de olika experimenten sämre
- Överensstämmelsen mellan de båda fullskaleförsöken (Runehamar och Memorialtunneln) och modellförsöken utförda av SP (Ingason) är relativt bra
- Resultaten från modellförsöken utförda av FOA-SP skiljer sig från de övriga försöken
- Resultaten från fullskaleförsöken indikerar att det inte finns någon tydlig övergång mellan region I och region II när temperaturkvoterna studeras
- I rapporten presenteras en ny korrelation för att beräkna golvtemperatur respektive taktemperatur på olika avstånd från branden baserad på de två fullskaleförsöken och ett modellförsök

# Innehållsförteckning

# Temperature stratification in tunnels

## Abstract
An investigation of previously established correlations between gas temperature distribution and smoke stratification in mines has been carried out for tunnel applications. The investigated correlations are based on excess gas temperature ratios and Froude number scaling. This paper describes a comparison between two large scale tests carried out in a road tunnel and two well defined model scale tests. In all the tests, a longitudinal flow was maintained. The temperature data obtained at different locations and different heights was used for the comparison. A good correspondence between the experimental data and the correlations was found when the gas temperature data was used. However, the correspondence between the previously established correlation of gas temperature stratification and Froude number, did not work very well. It is postulated that the main reason may be the way the experiments were carried out. New correlations between the temperature stratification and the Froude number are also explored.

Keywords: gas temperature, stratification, tunnel, ventilation, model scale tunnel

## Nomenclature

| | |
|---|---|
| Fr | Froude number |
| $g$ | acceleration of gravity (m/s$^2$) |
| $H$ | ceiling height (m) |
| $\Delta T_{avg}$ | temperature difference between the average temperature $T_{avg}$ and ambient temperature $T_a$ |
| $\Delta T_{cf}$ | temperature difference between the ceiling temperature $T_h$ and the floor temperature $T_f$ |
| $\Delta T_h$ | temperature difference between the ceiling temperature $T_h$ and the ambient temperature $T_a$ |
| $T_a$ | ambient temperature |
| $T_{avg}$ | average temperature |
| $T_f$ | floor temperature |
| $u_{avg}$ | average "hot" longitudinal velocity (m/s) |
| $u_0$ | average "cold" longitudinal velocity |
| $X_{i,h}$ | concentration of species $i$ at height $h$ |
| $X_{i,avg}$ | average concentration of species $i$ |

## Introduction
Newman [1] developed Froude number based correlations for mines in order to determine a ceiling temperature and a floor temperature related to an average temperature at different locations downstream from a fire source. Gas temperatures at three different elevations can be calculated in a tunnel cross-section and at a given position from a fire. CFD (Computational Fluid Dynamics) is usually used to calculate such temperature stratification in tunnels but it is desirable to be able to use simplified methods for both the analysis of different fire scenarios

and as an easy way to check whether the CFD calculations are reasonable. Therefore, methods like the one proposed by Newman [1] can be very useful as an alternative to one dimensional methods or CFD calculations.

There are numerous applications that are of interest for such correlations, provided their applicability to tunnels can be confirmed. In case of a fire in a tunnel, early detection is important. Usually detectors or sprinkler heads are located at or close to the ceiling, and if one want to calculate the response of such devices, the ceiling temperature at different distances from the fire is important. A one dimensional approach is too imprecise for such calculations, and CFD calculations may be too time consuming, a Froude number approach represents a happy medium.

Another example is calculation of hazardous conditions for tunnels users. In such calculations, it is the Available Safe Egress Time (ASET), related to the fire development (gas temperature and smoke spread), which is of greatest interest. In FID-calculations (Fraction Incapacitation Dose) [2] the effects of the smoke and gas temperature on human being are calculated and compared to a number of criteria. These criteria include the dose of CO, $CO_2$ and other toxic gases, together with the accumulated effect of heat, based on gas temperatures. The work by Ingason [3], make it possible to correlate gas temperatures and gas concentrations. Therefore, with a refined method of temperature calculation, the FID-calculations would also be improved. The development of the fire and the smoke stratification must also be considered, together with the distance between the emergency exits and possible air movements inside the tunnel. The result of such estimations could for example be used when assessing the possibility of using fans successfully in an evacuation or a fire-fighting situation. To be effective the fire brigade must know the location of the fire and the conditions (gas temperatures, visibility etc.) in the tunnel, and around the fire. This requires suitable calculation methods in the planning stage as well as reliable detection systems in the tunnel.

To date adequate validation of Newman's correlations for tunnel applications has been lacking. This article presents results from a validation of correlations presented by Newman [1] applied to results from tunnel tests. Results from two model experiments performed by Ingason [7] , [11], the large scale tests conducted in the Runehamar tunnel [4, 5] and the Memorial tunnel fire tests [6] have been used to investigate the validity of Newman's correlations.

## Theoretical aspects

Newman [1] presented results from fire tests performed in a medium-scale mine passage (duct). The rationale behind the tests was the study smoke stratification in mine fires. Newman's starting point was that the temperature stratification can be described by a Froude number and that the transport of chemical compounds follows the temperature rise. These assumptions can be summarised in equations (1) and (2):

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = f(Fr) \qquad (1)$$

$$\frac{X_{i,h}}{X_{i,avg}} = \frac{\Delta T_h}{\Delta T_{avg}} \qquad (2)$$

103353

Where $\Delta T_{cf}$ is the temperature difference between a ceiling temperature (at the height 0,88×H from floor) and a floor temperature (at 0,12×H from floor) related to the stratification, and $\Delta T_{avg}$ is the temperature difference between an average temperature in the cross-section and the ambient temperature. The parameter $X_{i,h}$ is the concentration of a species *i* at height *h*, and $X_{i,avg}$ is the average concentration of species *i*. In previous work by Ingason [3], the relationship given by equation (2) has been validated with good results. The present article focuses on comparisons using equation (1).

Newman [1] proposes three smoke stratification regions defined by the Froude number (Fr) and temperature quotients (see Figure 1), i.e.:

- Region I (Fr<0,9): clear stratification is distinguished.
- Region II (0,9<Fr<10): the smoke stratification is less severe
- Region III (Fr<10): there is no clear stratification.

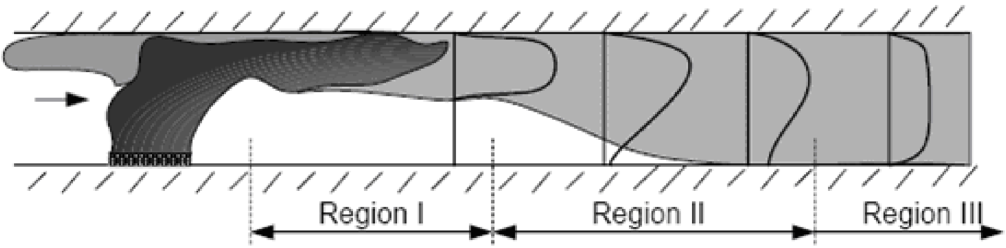


*Figure 1. A sketch from Ingason [10] showing the three regions proposed by Newman [1].*

Newman describes Region I as associated with low Froude numbers, i.e., buoyancy dominates temperature stratification. In Region 1 hot combustion products travel along the ceiling and the gas temperature near the floor is essentially ambient. Region II is governed by large Froude numbers, i.e., there is a significant interaction of the ventilation velocity with the fire-induced buoyancy. Although not severely stratified or layered it is mixture-controlled and it involves vertical temperature gradients. Region III shows insignificant stratification, i.e., the temperature profile is close to homogeneous with insignificant vertical temperature gradients. The Newman approximation is illustrated in two diagrams (see Figure 2 and Figure 3). In Figure 2, the relationship between two temperature quotations, the temperature difference between the ceiling and the floor ($\Delta T_{cf}$) and the temperature difference between the ceiling and the ambient temperature ($\Delta T_h$), is illustrated. On the y-axis, the quotient of the temperature difference between floor and ceiling ($\Delta T_{cf}$) and that between the ceiling and the ambient temperature ($\Delta T_{avg}$), is plotted. The data in Figure 2 show two distinct regions: (1) Region I, $\Delta T_{cf}/\Delta T_{avg}$ >1.7; and (2) Region II, $\Delta T_{cf}/\Delta T_{avg} \leq 1.7$. Region II is calculated using the following equation:

$$\frac{\Delta T_{cf}}{\Delta T_h} = 0{,}67\left[\frac{\Delta T_{cf}}{\Delta T_{avg}}\right]^{0{,}77} \qquad (3)$$

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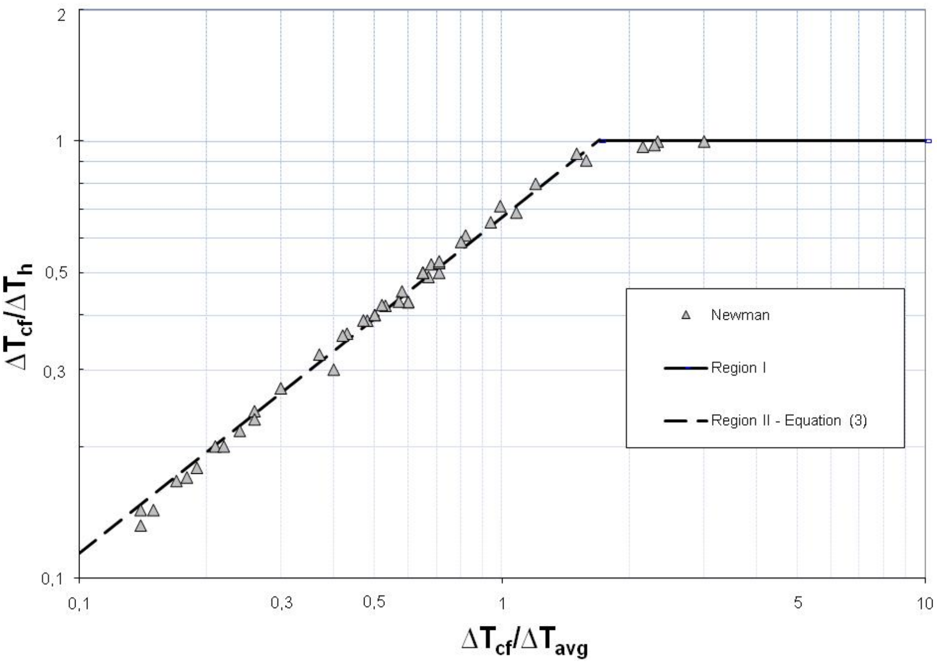


*Figure 2. Temperature stratification as presented by Newman [1].*

In Figure 3, $\Delta T_{cf} / \Delta T_{avg}$ is studied as a function of the Froude number. The Froude number is defined as:

$$Fr = \frac{u_{avg}}{\sqrt{\frac{\Delta T_{cf}}{T_{avg}} gH}} \qquad (4)$$

where the velocity $u_{avg}$ is the "hot" velocity across the cross-section and on the downstream side of the fire. The results in Figure 3, plotted in a log-log graph, suggest the following relationship with a correlation coefficient of $r^2$=0.90:

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = 1{,}5 Fr^{-1} \qquad (5)$$

where $u_{avg} = T_{avg} / T_a / u_0$ in equation (4) and (5), and $u_0$ is the "cold" velocity on the upstream side of the fire.

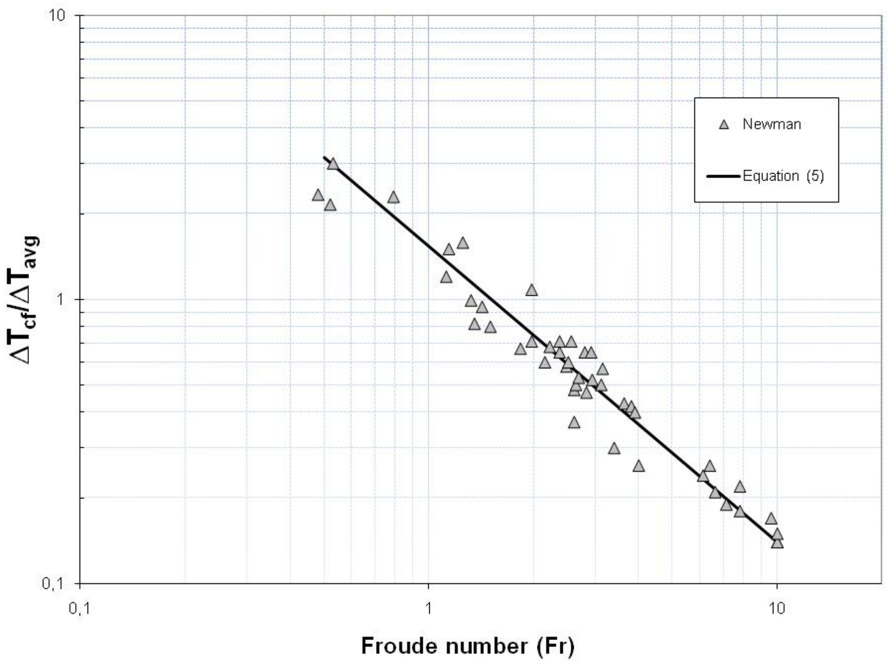


*Figure 3. Newman's gas temperature stratification versus Froude number [1].*

From the curve plots for the different regions, equations for gas temperatures can be derived. Newman found three regions analogous to those given previously observed in Figure 2. Newman defined a "critical" Froude number, $Fr = 0{,}9$, which can be specified as the boundary between the first two regions, i.e., Region I and II, where $\Delta T_{cf} / \Delta T_{avg} = 1.7$. Below this value, $\Delta T_{cf} \approx \Delta T_h$, as previously shown for Region I where $\Delta T_{cf} / \Delta T_h \approx 1$. Consequently, only two parameters determine the stratification, $\Delta T_h$ and $\Delta T_{avg}$, in Region I. Region II is bounded by $0.9<Fr<10$, where $\Delta T_{cf}$, $\Delta T_h$ and $\Delta T_{avg}$ are all necessary to determine the degree of stratification. For $Fr \geq 10$, stratification is insignificant according to Newman, i.e., $\Delta T_h \approx \Delta T_{avg}$. Newman expressed two correlations for $\Delta T_h$, one for Region I and one for Region II. Using Equation (3) and $\Delta T_{cf} \approx \Delta T_h$, $\Delta T_h$ can be expressed for Region I as :

$$\Delta T_h = \frac{2{,}25gH}{T_{avg}} \left[ \frac{\Delta T_{avg}}{u_{avg}^2} \right]^2 \qquad (6)$$

and for Region II, using equations (3), (4) and (5), we obtain:

$$\Delta T_h = 1{,}8 \left[ \frac{gH}{T_{avg} u_{avg}^2} \right]^{0{,}23} \Delta T_{avg}^{1{,}23} \qquad (7)$$

The correlations given by equations (3), (4), (5) and (7) will be used for plotting the experimental data obtained from the fire tests using longitudinal ventilation. In the following section, a brief description of Newman's [1, 12] experimental duct tests, and the model scale tests [7, 11] and large scale tests [4, 5] by Ingason et al. are given.

## Experimental aspects

**Newman duct experiments [1, 12]**

Newman performed experiments in a large-scale duct that measured 46,7 m × 2,4 m × 2,4 m, and with a T-section of 45,8 m as shown in Figure 4. The duct was designed to simulate conditions in underground mine passages. In the tests, the fire size and the longitudinal velocity varied. The ventilated air entered the duct through an inlet orifice contained in a flow straightening section and was exhausted through an exhaust duct connected to an air pollution control system. The fire source was placed at the location indicated by N-3 in Figure 4.

The analysis is based on the measured average temperature in the cross-section, two locally measured temperatures, a ceiling temperature at height 0,88H and a floor temperature at 0,12H, where H is the height of the tunnel. The instrument stations were located at N-5, N-11, N-19, E-1, with a distance varying in length to height (l/H) ratio of 2 to 22, respectively. The fire source consisted of 12 heptane pan fires, one fire with coal ignited by kerosene (0,61 × 0,61 × 0,1 m square pile), one fire with coal (0,61 × 0,61 × 0,1 m) and neoprene conveyor belting (0,07 × 1,52 × 0,01 m) and one methanol pan fire (0,31 m × 0,31 m) with neoprene conveyor belting [12]. Data from tests by Litton et al. [13] consisting of oil Shale Rubble were also used in the analysis by Newman. The heat release rates from the various fire sources ranged between 10 kW and 20 MW. The ventilation air velocity was varied between 0.5 and 4 m/s. More detailed information on the test setup and test data is found in [12].

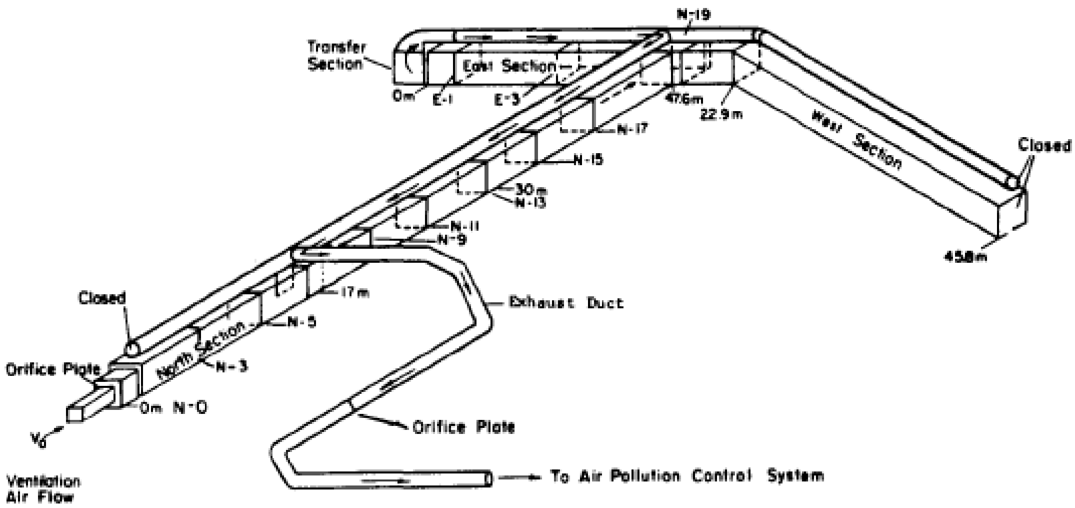


*Figure 4. Schematic of Newman's large- scale duct set-up* [1].

**FOA-SP model scale tests [7]**

Ingason and Werling [7] (FOA-SP) carried out fire tests in a 20 meter long small scale model tunnel 1 m high and 2 m wide, see Figure 5. The scale of the tunnel was assumed to be 1:8. One side of the tunnel was made of fire proof glass so the smoke stratification could be observed and documented. In the tunnel there were also a number of ventilation shafts that could be opened to evacuate smoke. In the present paper the tests conducted with ventilations shafts closed, are considered.

In the report the cross-sectional temperatures at different distances from the fire are presented. In the experiment the longitudinal velocity, and to a certain degree the fire size, varied. The temperatures were measured at four places down stream the fire (D, E, F, G) and at the distances 0,1, 0,3, 0,5, 0,8, 0,9 meters from the floor of the tunnel. Six tests (test 18, 19, 20, 22, 23 and 24) with ventilation shafts closed were used for the analysis of Newman's correlations. The longitudinal velocities in these tests were 0,5 m/s, 0,75 m/s, 1 m/s and the fire size varied from 30 to 80 kW. The temperature data and the velocity data was obtained from average values during the test performed at three different locations (E, F and G).

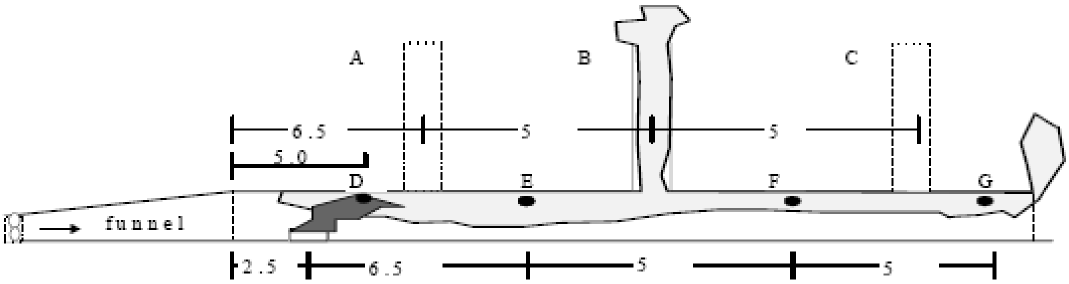


*Figure 5. The FOA-SP experimental set up. All dimensions are in meter [7].*

**Ingason- model scale tests [11]**

Ingason [11] performed fire tests in a 1:23 scale model tunnel, as shown in Figure 6. The parameters tested were: the number of wood cribs, the type of wood crib, the longitudinal ventilation velocity and the ceiling height.

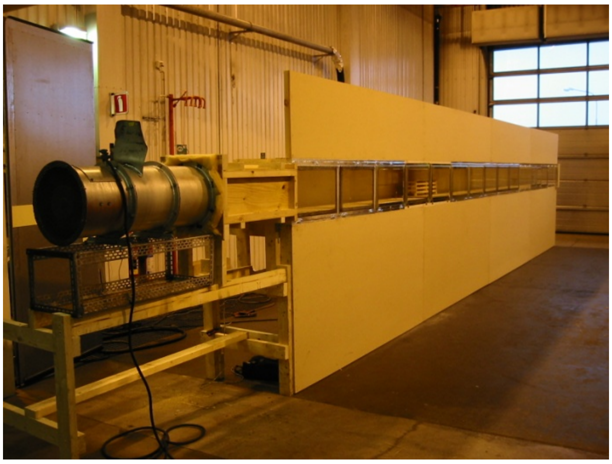

*Figure 6. A photo of the 1:23 model-scale tunnel from tests performed by Ingason [11]. A fan was attached to the tunnel entrance and windows were placed along one side in order to observe the smoke flow.*

The tunnel was 10 m long, 0,4 m wide and with two heights, 0,2 m and 0,3 m. Longitudinal flow was supplied using an electrical axial fan attached to the entrance of the model tunnel. The maximum heat release rates in the experiments were 80-110 kW and the velocity varied between 0,5-1 m/s. Various measurements were conducted during each test. The HRR was measured by weighing platform. The temperature was measured with welded 0.25 mm type K thermocouples (T). Most of the thermocouples were placed along the ceiling at a distance of 0.035 m from the ceiling. A set of thermocouples was placed 6.22 m (stack A) and 8.72 m from the inlet opening (stack B). The thermocouples in each set were place in the centre of the tunnel and 0.036 m, 0.093 m, 0.15 m, 0.207 m and 0.265 m above the floor. The velocity was measured at the centreline of the tunnel 8.72 m from the inlet (at stack B). Another bidirectional probe was placed upstream the fire at the centre of the cross-section and 2.165 m (B21)

In the present study, three tests are selected for the analysis of Newman's correlations: Test 1, with longitudinal ventilation rate of 0,64 m/s; Test 6, with longitudinal ventilation rate of 0,52 m/s; and Test 8, with longitudinal ventilation rate of 0,47 m/s. Temperature values from stack A were used, as well as the velocity on the upstream side. The velocity on the downstream side at stack A, was calculated using temperature data at stack A. The tunnel width in these tests was 0,4 m and the tunnel height was 0,3 m [11]. In all these three tests, only a single wood crib was used as the fire source in each test.

**Runehamar-large scale tests [4, 5]**
Four large-scale fire tests (T1, T2, T3 and T4) were performed with a mock-up of a heavy goods vehicle (HGV) trailer in the Runehamar tunnel in Norway [4, 5]. Different mixtures of cellulose and plastics (approximately 18% plastics in each test) were used as fuels. In test T1, the fuel consisted of wood and plastic pallets, in test T2 of wood pallets and PUR-mattresses, in tests T3 of furniture and fixtures and in T4 of corrugated cardboard and plastic cups. Two mobile fans were stationed at the tunnel mouth, and together generated an air flow velocity of over 3 m/s through the tunnel. The HRR was determined from measurements at an instrument station located 458 m downstream of the fire. The maximum HRR of the first test (wooden and plastic pallets) was 202 MW, for T2 it was 157 MW, for T3 it was 119 MW and for T4 it was 66 MW. The growth rate was relatively linear from 5 MW up to 100 MW, varying from 17 MW/minute to 29 MW/minute, with the most rapid rate of fire growth occurring in T2.

The tunnel was 1600 m long, 6 m high and 9 m wide. The incline of the tunnel varied between 0.5% uphill and 1% downhill. The fire was located on the downhill portion of the tunnel. Temperatures were measured at several positions along the tunnel, from 100 m upstream of the fire ('-100 m') to a measurement station 458 m downstream of the fire ('+458 m'), i.e. approximately 100 m from the west entrance. The majority of the temperatures were measured using unsheathed thermocouples, 0.25 mm type K. The temperature 458 m from the fire was determined at five different heights: 0.7 m, 1.8 m, 2.9 m, 4 m, and 5.1 m above the road surface as shown in Figure 7.

Data from the measurement station at +458 m from the fire source was used to investigate the influence of different ways of calculating the $T_{avg}$ and $\Delta T_{avg}$. Therefore, the layout of the instrument station used for this purpose is shown in Figure 7.

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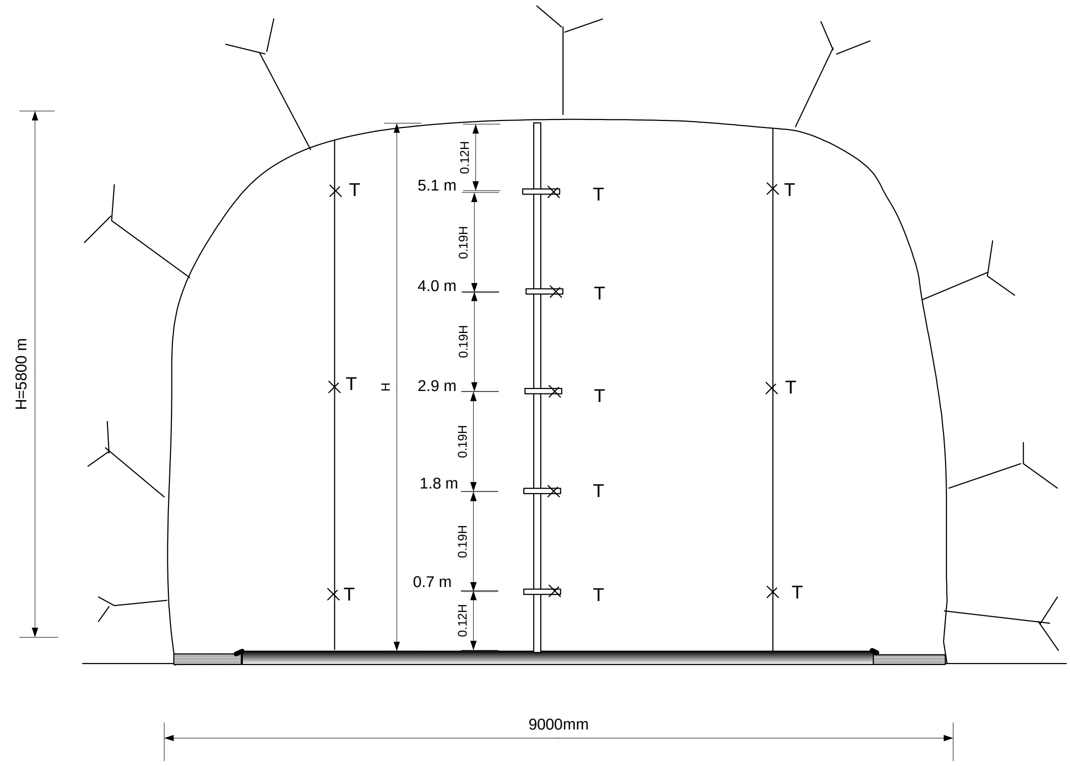


*Figure 7. The Runehamar measurement station 458 m downstream the fire [4]. T=gas temperature at elevations 0.7 m, 1.8 m, 2.9 m, 4.0 m, and 5.1 m.*

**Memorial – large scale tests [6]**
The Memorial Tunnel Fire Ventilation Tests [6] consisted of series of large-scale fire tests carried out in an abandoned road tunnel. The fire source consisted of low sulphur No2 fuel oil pans (diesel) and mock-up vehicles. Various tunnel ventilation systems and configurations were operated to evaluate their respective smoke and temperature management capabilities. The test program was performed in a two-lane, 853 m long and 8,8 m wide road tunnel. The tunnel had a 3,2 % upgrade from south to north portal. The tunnel was originally designed with a transverse ventilation system, consisting of a supply fan chamber at the south portal and an exhaust fan chamber at the north portal. An overhead air duct, formed by a concrete ceiling 4,3 m above the roadway, was split into supply and exhaust section by a vertical concrete dividing wall. In some of the tests, the horizontal ceiling was removed in order to install 24 reversible jet fans, in groups of three, equally spaced over the tunnel. In these tests the cross-section changed from rectangular shape with cross-sectional area of 36,2 m$^2$ to more of a horse shoe shape with a height of 7,9 m and a cross-sectional area of 60,4 m$^2$. Comprehensive instrumentation was located both up and downstream of the fire.

In the analysis of Newman's correlations, the tests with longitudinal ventilation were used. The tests used are Test 605 with 2,2 m/s longitudinal flow rate and nominal 10 MW fire, Test 607 with 2,1 m/s flow rate and nominal 20 MW fire, Test 624B with 2,3 m/s and nominal 50 MW fire and Test 625B with 2,2 m/s flow rate and nominal 100 MW fire. The ceiling height in all these tests was 7,9 m and the width was 8,8 m.

## Analysis

The analysis of the data from the FOA-SP, Ingason model scale tests and the large scale tests in Runehamar and Memorial tunnel was carried out using the two correlations presented by Newman in equations (3) and (5). The data from the model and larges scale tests are plotted

103353

together with the results from Newman's duct tests [1] in Figures 8 and 9. The data points used in the analysis have all been selected some time after the fire ignition when the temperature increase at the test site is clear.

The average gas temperatures, $T_{avg}$ and $\Delta T_{avg}$, were calculated as the arithmetic average of the measured gas temperatures in each cross-section and location in the tunnel. The calculation of the average temperature can vary depending on the number of temperature data points. In the Runehamar tests the temperatures were measured at 1.8 meters and 5.1 meters, respectively and at a number of different distances from the fire. There was only one place (458 meters from the fire) where the temperature were measured at different elevations over the whole cross-section (see Figure 7). If a simpler definition of the average temperature could be used more measurement data could be used to verify the Newman's method. In cases where multiple readings for height are available, the arithmetic means were used, but it is also possible to use the average between the ceiling and floor temperature. In Newman's article it is not clear how the average value was calculated.

To investigate this, a short analysis using the extensive instrumentation in the Runehamar tests at 458 m from the fire, was used. The temperatures were measured at 11 points over the whole cross-section (see Figure 7). In the first experiment, T1, the arithmetic mean based on 11 points, 15 minutes after ignition, was 89.4 ° C. Based on five points at the centreline column in Figure 7, the average is 84.0 ° C. If the average temperature is calculated as the average between 0.88 H and 0.12 H (one ceiling temperature and one floor temperature), the average temperature becomes 96.4 ° C. If the average is calculated as the value between a ceiling temperature at height 0.88 H and a temperature situated at 1.8 m above the floor, the value is 103.4 ° C. The maximum difference between the different methods used to calculate the average temperature is 8%. Similar results are obtained when comparing the mean temperatures for tests T2, T3 and T4 in the Runehamar test series. The largest percentage difference between the simplified methods to calculate the average temperature and the arithmetic average is around 11%. This means that average temperatures based on two points only differs by about 10% compared to the average temperatures based on many more points.

The first correlation, given by equation (3), has been plotted using the test data and calculated average temperatures. In Figure 8 the measured temperatures ratios, $\Delta T_{cf} / \Delta T_h$, versus $\Delta T_{cf} / \Delta T_{avg}$ are shown. Newman's curve plot approximation for Region I and Region II are also presented. In the original data from reference [12] there is one data point that obtains a value of $\Delta T_{cf} / \Delta T_{avg}$ =1,33 and $\Delta T_{cf} / \Delta T_h$ =0,8. This value is not found in Figure 2, and is clearly out of the range of all the other data. This point has been excluded here, mainly because Newman has not included it in his original graph (figure 2) and because it clearly does not comply with the rest of the data.

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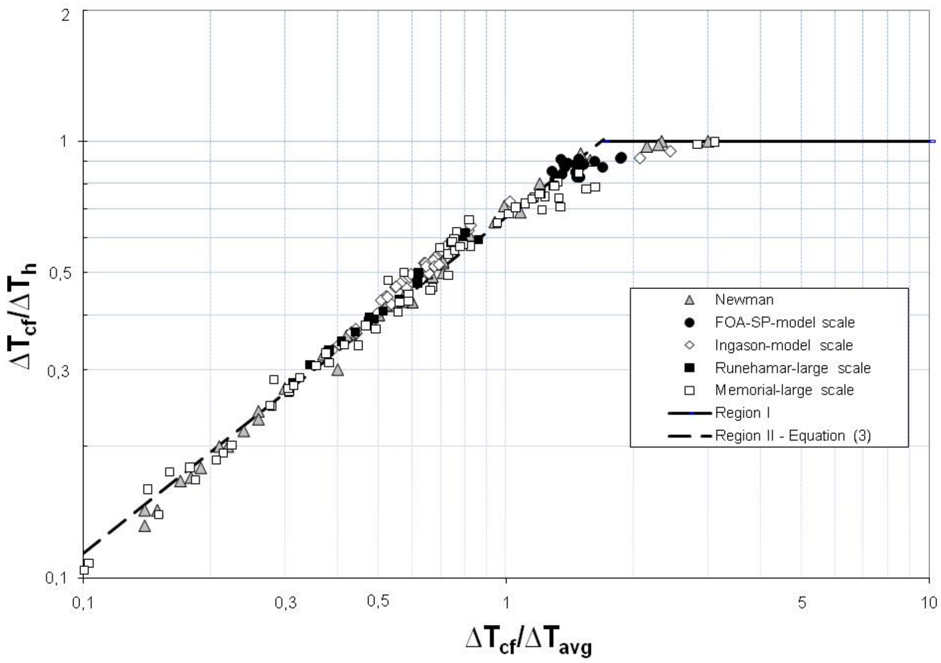


*Figure 8. The SP/FOA-tests presented in Newman's temperature diagram.*

The temperature ratio data from the model scale experiment and the two full-scale experiments corresponds well with Newman's experiments. This means that equation (3) for Region II, represents the experimental gas temperature data very well and can therefore be used for this type of temperature correlations for temperature stratification in tunnels. The values from the Runehamar tests and the majority of the data from the Memorial tunnel tests are located in Region II. In the model scale tests, minor spread in the data is concentrated to Region I area and close to the Region II. Few data points from the Memorial tests, Ingason tests and Newman's tests are found in Region I. The Newman definition of Region I is the break point when the temperature ratio $\Delta T_{cf} / \Delta T_h = 1$, i.e. the temperature near the floor is approximately equal to the ambient temperature $T_f \approx T_a$ (or $\Delta T_{cf} \approx \Delta T_h$). This corresponds to $\Delta T_{cf} / \Delta T_{avg} \approx 1{,}7$ as can be observed in Figure 2 and Figure 8. Region I in Figure 8 is distinguished by a clear temperature stratification where the floor temperature is approximately equal to the ambient temperature, $T_f \approx T_a$ (or $\Delta T_{cf} \approx \Delta T_h$). This constant region can be approximated theoretically by making some assumptions about the average temperature. Assuming that $T_f \approx T_a$, the ratio $\Delta T_{cf} / \Delta T_{avg}$ can then be written as:

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = \frac{T_h - T_f}{T_{avg} - T_a} \approx \frac{T_h - T_a}{T_{avg} - T_a} \approx \frac{\Delta T_h}{\Delta T_{avg}}$$

103353

It can be shown, if analysing the experimental data, that a reasonable assumption of the average temperature within Region I is $T_{avg} \approx \frac{T_h + T_a}{2}$. This means that ratio $\Delta T_h / \Delta T_{avg}$ can be written as $\frac{T_h - T_a}{T_{avg} - T_a} = \frac{T_h - T_a}{\frac{T_h + T_a}{2} - T_a} = 2$

In summary, $\Delta T_h / \Delta T_{avg} \approx \Delta T_{cf} / \Delta T_{avg}$ in Region I should be constant and depend on the definition of the average temperature. The equation can also be written as $\Delta T_h = 2T_{avg} - T_a$. This value is quite close to the experimentally obtained value of 1.7, which indicates that this area should be relatively constant as shown in Figure 8.

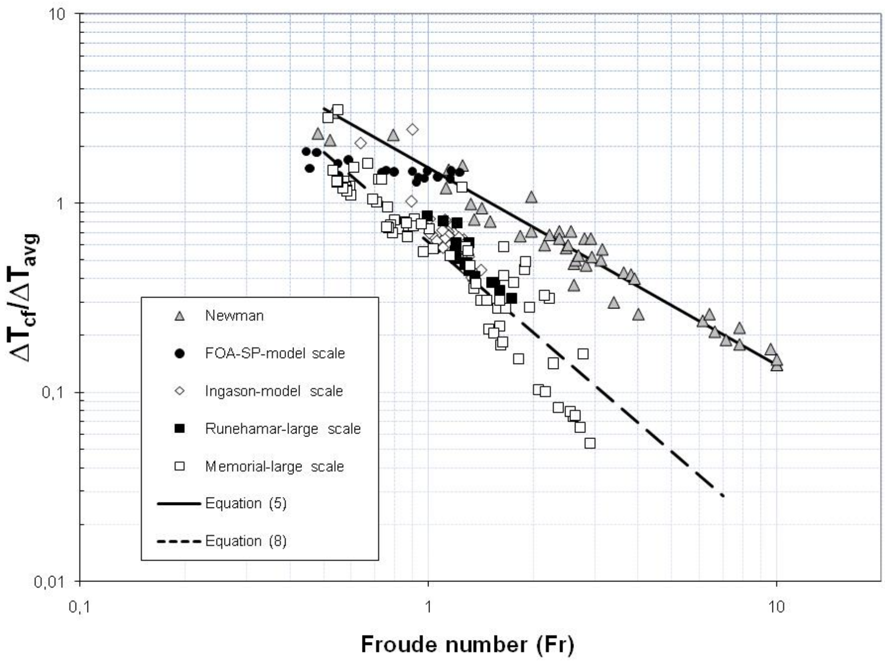


*Figure 9 Tests presented in a Temperature – Froude number diagram.*

The ratio $\Delta T_{cf} / \Delta T_{avg}$ has been plotted as a function of the *Fr* number defined according to equation (4). The data from Newman, the FOA-SP/Ingason model scale tests together with large scale tests in the Runehamar and Memorial tunnel are shown in a log-log graph in Figure 9.

The data from the Runehamar and Memorial large scale test series are relatively close to each other but diverge from Newman's results. The models scale data from Ingason, also falls nicely on the data from Runehmar and Memorial tunnel tests. The slope is steeper and the data is more scatter than Newman’s data. A curve fit of the data from Ingason, Runehamar and Memorial yields the following equation:

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = 0{,}62 \cdot Fr^{-1{,}58} \qquad (8)$$

103353

with a correlation coefficient of $r^2$=0.86. This correlation appears to be valid for both Region I up to Fr>0.4 and for Region II.

In Figure 9, it can be observed that there is a poor correspondence between the FOA-SP tests and the other tests including Newman's data. The slope differs considerably from the other data. The FOA-SP data actually follow the same slope in a range between Fr=0,45 and F=1,2. As with the Memorial tests, these tests are quasi-steady state as the heat release rate is relatively constant and the temperature and velocity profiles can be fully developed within the test period. The Runehamar tests and the model scale tests performed by Ingason were transient tests, i.e. the heat release rates changed with time. This may explain why there is a difference in the results as the establishment of the flow profile may be very different depending on whether the test is transient or steady state. This does not explain why the Memorial tunnel tests follow the trend of Runehamar large scale data and Ingason model scale data. Further research is needed to establish a plausible explanation for the differences in Newman's test data, FOA-SP data and the other test data.

The values that have been used in figures 8 and 9 have all been chosen when a clear increase in temperature (> 20 $^o$C) has occurred in the measuring points. This applies to both the full-scale tests and the model-scale tests. Although the ratio $\Delta T_{cf} / \Delta T_{avg}$ does not change significantly, the Froude number will if gas temperature values are taken from the early stage of the fire, according to equation (5). The Froude number can easily change from 20 down to about 1 or 2, when the ratio $\Delta T_{cf} / \Delta T_{avg}$ starts to comply with equation (8). This movement in the early stage of the fire has also been observed in the data from the Memorial tunnel. This behavior of the Fr number is related to the fact that when $\Delta T_{cf}$ is very small, the Fr number is very sensitive and becomes large, while the ratio $\Delta T_{cf} / \Delta T_{avg}$ is not sensitive and stays at a relatively constant level.

The final correlation that was investigated is equation (7) for Region II. The initial problems with $\Delta T_{cf}$ disappears here as we only use average temperatures and velocity. The data has been plotted in the same manner as previously, using equation (7) on the ordinate and $\Delta T_h$ on the abscissa. The results are shown in Figure 10, together with Newman's data. The data from the small scale test by Ingason, Runehamar and the Memorial tunnel tests do not comply with Newman's data.

103353

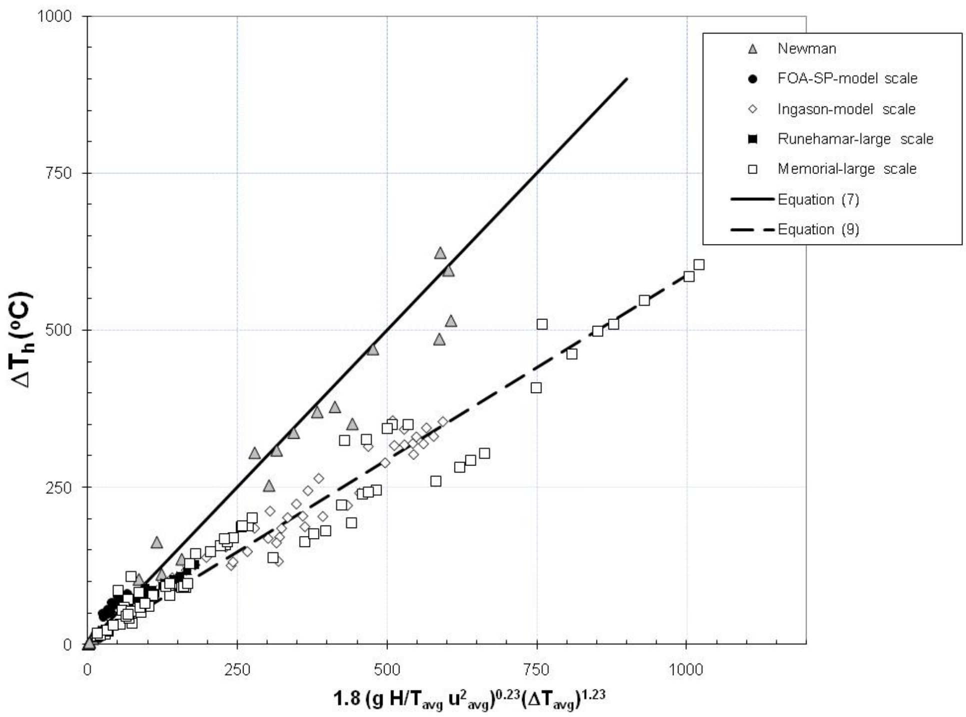


*Figure 10. The temperature difference $\Delta T_h$ plotted according to equation (7).*

A curve fit of the data from Ingason, Runehamar and Memorial yields the following equation

$$\Delta T_h = 1{,}06\left[\frac{gH}{T_{avg}u_{avg}^2}\right]^{0,23}\Delta T_{avg}^{1,23} \qquad (9)$$

with a correlation coefficient $r^2$=0,946 which is considerably better correlation of the data compared to equation (8). With knowledge of $\Delta T_h$ we can easily obtain $\Delta T_{cf}$ with aid of equation (3) and (9), or

$$\Delta T_{cf} = 0.225\left[\frac{gH}{T_{avg}u_{avg}^2}\right]\Delta T_{avg}^2 \qquad (10)$$

If we know the average temperatures, $T_{avg}$ and $\Delta T_{avg}$ at a certain position from the fire, and the average hot velocity, $u_{avg}$, we can easily calculate the ceiling temperature $T_h$ and the floor temperature $T_f$ using equations (9) and (10). This means that we have knowledge of gas temperatures at three levels in a cross-section, one at 0.88 H, one at 0.5 H and one at 0.12 H.

## Discussion

On the basis of correlations suggested by Newman, full-scale tests from the Runehamar tunnel, the Memorial tunnel and model-scale tests that were performed by FOA-SP and Ingason [4] have been analysed. From a calculated average temperature downstream a fire in a tunnel and a Froude number different regions, ceiling temperature and floor temperature can be calculated.

The results suggest that the ratio $\Delta T_{cf}/\Delta T_{avg}$ can be described as a piecewise function in two regions: Region I (with clear stratification) and Region II (with less clear stratification). The analysis of the tests show that $\Delta T_{cf}/\Delta T_{avg} \approx 1{,}7$ is consistent with Newman's tests and the theoretical value obtained earlier i.e. $\Delta T_{cf}/\Delta T_{avg} \approx 2$. The analysis of the two large-scale experiments and Ingason's [4] model scale tests indicate that the data corresponds to a Froude number equal to about 0,55 which is lower than that proposed by Newman (Fr = 0,9). The analysis also shows the importance of correct calculation of average temperatures, $T_{avg}$ and $\Delta T_{avg}$, downstream the fire.

This means that with a calculated average temperature and average velocity, gas temperatures in the ceiling and floor level can be estimated using Figures 8 - 10 or equations (9) and (10). The analysis also shows that the results must be used with caution, taking into account differences in geometry, air velocity and the fire development in different situations.

An aspect concerning transient development is that the temperature and velocity profiles can be different in a steady-state conditions and steady-state-like conditions. This may affect the ratio $\Delta T_{cf}/\Delta T_{avg}$ and thus also the temperature-Froude-graphs, see Figure 9. The velocity profile can also affect the results since the average velocity is part of the Froude number and the velocity profile in Regions I and II are different.

In summary, one can say that both the temperature profile and velocity profile may influence the results depending on whether the fire development is transient or steady state. Further, the definition of the Froude number may in some cases affect the results. There is still a need for further validation of the correlations obtained here, and to give a better explanation of why there is a difference in the results obtained when an average "hot" velocity is introduced.

## Conclusions

There is a need for a correlation to estimate the temperature stratification in a tunnel fire based on an average temperature and an average velocity at a certain position downstream of the fire .The results of the analysis where full-scale tests performed in Runehamar, the Memorial tunnel, and model-scale experiments are compared with experiments and correlations proposed by Newman reveals the following:

- If the temperature ratios alone are studied in the different tests the results show a good correspondence to Newman's correlation.

- When the Froude number is introduced into the analysis, the correlation between the different experiments is not as good. However, the results from the two full-scale experiments (Runehamar and the Memorial tunnel) and the model scale tests by Ingason agree relatively well.

- The FOA-SP model scale tests exhibit different behavior relative to the correlations given by Newman. No explanation has presently been found for this behavior.

- The results of the full-scale experiments indicate no change between Regions I and II when plotting temperature ratio versus the Fr number. A good correlation is found for the data from Froude number (Fr = 0.55) up to Fr=3.

- In the Runehamar tests the average temperature in a cross-section was calculated in a number of ways. The results showed average temperatures based on two points only, differ by about 10% from the average temperatures based on many more points in a cross-section.

- The results are most likely dependent on whether the tests can be characterized as transient or steady state.

- This article proposes new correlations for the calculation of the ceiling and floor temperatures at different locations based on the two full-scale experiments and one model scale test series. These correlations should be used with caution because the results suggest that the described processes are complex. Further validation of these correlations is needed.

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103353