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Temperature property of ceiling jet in an inclined tunnel

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Abstract

The properties of a ceiling jet flow confined by the sidewall of an inclined ceiling differ from those of a flow in a horizontal tunnel and under an unconfined ceiling. However, few studies have focused on the flow property in an inclined tunnel. In this study, we conducted a series of fire tests using a 1/23.3-scale model tunnel with dimensions of 3.6 m (L) × 0.55 m (W) × 0.30 m (H) for various tunnel inclination angles of up to 20°. The model tunnel has a rectangular cross section and its aspect ratio is 1:2. Two types of fire heat release rates were used assuming vehicular fires in a passenger vehicle or a bus. The maximum temperature rise of the smoke layer near the ceiling and its position, Gaussian thermal thickness, and temperature properties from the plume impingement point along the steepest run in the upward direction were compared with the results obtained in a horizontal tunnel with longitudinal ventilation and an inclined unconfined ceiling.

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Keywords: Ceiling jet; Inclined tunnel; Maximum temperature rise and its position; Gaussian thermal thickness; Temperature rise decreasing

Nomenclature

A_f	area of fire source (m^2)
A_S	cross-sectional area of model tunnel (m^2)
b	model tunnel width (m)
D_2	length of fire source perpendicular to the flow direction of inflow ventilation (m)
Fr	Froude number (-) $Fr = U^2/(gH)$
g	acceleration due to gravity (m/s^2)
H	tunnel height (m)
H_d	height from surface of fire source to tunnel ceiling (m)
L	length of the straight line connecting the maximum temperature position and the centre of the fire source (m)
L_{bl}	backing-up layer distance (m)
L_t	Gaussian thermal thickness (m)
T_∞	temperature in atmosphere (K)
$\dot{Q}$	heat release rate (kW)

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Q^*	dimensionless heat release rate (-) $Q^* = \dot{Q}/(\rho_\infty C_p T_\infty g^{1/2} H^{5/2})$
ΔT	temperature rise (K)
r	distance from the fire source along the tunnel axis (m)
U	representative velocity of air that flows into model tunnel (m/s) $U = V/A_S$
V	amount of inflow air (m^3/s)
Greek symbols	
α, β	coefficients
η	coefficient determined in each region: $\eta = -1/3$ (Region I), $\eta = 0$ (Region II), $\eta = 1/2$ (Region III)
θ	inclination angle of tunnel (°)
ρ_∞	density of air (kg/m^3)
Subscripts	
max	maximum
T	total

1. Introduction

Tunnels are a common feature of road and railway networks used for passenger and cargo transportation. In such tunnels, fires are major hazards and their risks should be considered. Many studies on tunnel fires have focused on smoke control using a longitudinal ventilation system from the viewpoint of evacuation [1-6]. Others have focused on the temperature properties in the near field of a fire source and the flame shape from the viewpoint of fire resistance [7-12]. Now, most of these studies have targeted horizontal tunnels. However, deep subterranean tunnels have a ramped entrance, and the properties of the ceiling jet flow in such tunnels are considered to be different from those in a horizontal tunnel because of the inclination of the tunnel and the buoyancy of smoke. Unfortunately, few studies have focused on the flow property in an inclined tunnel [13, 14].

The current study aims to understand the temperature properties in an inclined tunnel through experiments. Toward this end, a series of fire tests were conducted in a model tunnel with dimensions of 3.6 m (L) × 0.55 m (W) × 0.30 m (H) for various inclination angles of up to 20° in order to understand the effect of the inclination angle on the flow properties of the ceiling jet.

2. Experimental approach

Figure 1 shows a schematic diagram of the experimental setup. The model tunnel had walls made of 25-mm-thick ceramic boards. As mentioned above, it had dimensions of 3.6 m (L) × 0.55 m (W) × 0.3 m (H). The inclination angle was set at 0°, 8°, 10° and 20 °.

When the model tunnel was inclined, the amount of fresh air flowing into it by the natural ventilation was measured by using an orifice flowmeter set at the air supply inlet side. The differential pressure at the orifice plate was measured by using a pressure transducer (DP103-06, Valydyne). The inlet air temperature was measured by using a copper-constantan thermocouple with a strand diameter of 0.2 mm. The exhaust side was left completely open to enable the unrestricted flow of the hot current.

The heat release rate was set as 1.95 and 5.78 kW, assuming vehicular fires in a full-scale passenger vehicle (5 MW) or bus (15 MW). The height of a full-scale tunnel was assumed to be 7 m. Liquefied petroleum gas was used as a fuel, and it was supplied to the diffusion gas burner through a mass flow controller (Model 3660, Kofloc). The gas burner was filled with fine porous aggregates, and it was positioned at a distance of 1.35 or 1.95 m from the exhaust opening depending on the inclination angle of the tunnel in order to prevent the front of the hot current backing-up to the air inlet opening from escaping the tunnel. The surface of the gas burner was flush with the tunnel floor and aligned with the tunnel axis.

The heat release rate was estimated from the amount of LPG combusted and the heat of combustion of the fuel, it was found to correspond to the value calculated by assuming complete combustion. The heat of combustion of propane was assumed to be 43.7 kJ/g [15].

The temperature of the smoke layer was measured using chromel-alumel and copper-constantan thermocouples. The strand diameter of both thermocouples was 0.20 mm. Chromel-alumel thermocouples were set in the near field of the fire source and copper-constantan thermocouples, in the far field. These thermocouples were installed along the tunnel axis at 5- or 10 cm intervals depending on the position at a distance of 10 mm below the tunnel ceiling.

The temperatures perpendicular to the inclined tunnel ceiling within the smoke layer that runs passing through the inclined ceiling centre produced by a steady fire source were measured using thermocouple rakes of chromel-alumel and copper-constantan. The measured temperatures include the effect of radiation from the flame and warmed boundaries.

Data were obtained by averaging for 3 – 4 min after ignition. This duration was chosen to achieve a quasi-steady state for both the heat release rate and the flow inside the tunnel. The data were logged at 1-s intervals by using a data logger (TDS-602 & SHW-110T, Tokyosokki), and the data were stored in a PC for further analysis. Data collection commenced 60 s before fuel ignition. During each test, the forced ventilation in the laboratory was blocked and all doors of the test room were closed.

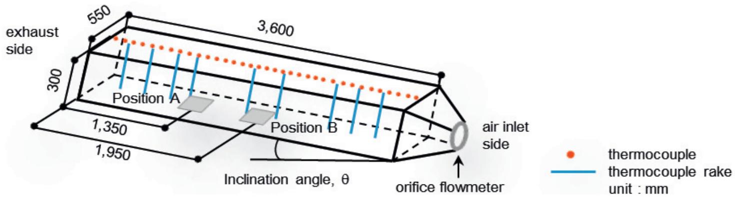


Fig. 1. Outline of experimental setup.

3. Results and discussions

3.1. Maximum temperature of smoke layer under tunnel ceiling and its position

The aim of this trial is to confirm whether the relations for estimating the maximum temperature and its position derived in a horizontal tunnel with longitudinal ventilation can be applied in an inclined tunnel; these parameters were adopted as the variables to show the temperature properties in the vicinity of the fire source. In other words, the longitudinal ventilation velocity was replaced with the representative mean velocity produced by the combinations of the buoyancy and the inclination of the tunnel. This representative mean velocity was calculated by dividing the measured total volumetric flow by the effective cross-sectional area of the tunnel. The total volumetric flow was calculated by multiplying the velocity at the orifice plate and the cross-sectional area of the orifice plate.

Equation (1) is an empirical formula for estimating the maximum temperature rise of the smoke layer for a horizontal ceiling with a longitudinal ventilation system [8]. The coefficients in the original correlation are listed in Table 1.

A comparison of the measured data obtained in an inclined tunnel and the predicted values obtained using Eq. (1) is shown in Fig. 2. Although the measured data shifted to the right of the line calculated using Eq. (1), the dependency of the maximum temperature rise on the *X* axis value is preserved. In other words, the power is maintained.

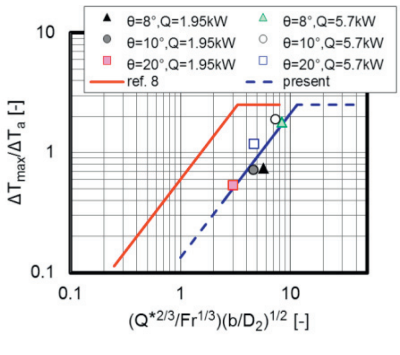


Fig. 2. Comparison of experimental results and predicted values of maximum temperature of smoke layer.

As the velocity of the flow resulting from natural ventilation in the inclining tunnel is much smaller than that of the flow resulting from mechanical forced ventilation, there is a difference between the measured data and the predictive value. The new values of the coefficients based on the measured data are listed in Table 1.

$$\frac{\Delta T_{\max}}{T_a} = \alpha_1 \left\{ \left(Q^{*2/3} / F_r^{1/3} \right) \times \left(b / D_2 \right)^{1/2} \right\}^{\beta_1} \tag{1}$$

The correlation shown in Eq. (2), can be used to predict the position at which the maximum temperature rise of the smoke layer appears in a horizontal tunnel with longitudinal ventilation [8]. This correlation was developed based on data that examined the influence of the fire source shape using a scaled tunnel having a cross section with an aspect ratio (ratio of the height to the width) of 1:2. The value of η in Eq. (2) varies depending on the maximum temperature rise of the smoke layer. The regions correspond to the relative position of the flame and the tunnel ceiling, which is described as follows. Region I corresponds to the situation in which the flame does not impinge on the tunnel ceiling; Region II, to the region between those of Regions I and III; and Region III, to the situation in which the flame completely impinges on the tunnel ceiling and extends in the upward and/or downward direction along the tunnel ceiling.

Table 1. Values of coefficients in Eq. (1)

	range of application	α_1	β_1
Ref [8]	$X < 3.3$	0.60	6/5
	$X \geq 3.3$	2.53	0
Present	$X < 11.56$	0.134	6/5
	$X \geq 11.56$	2.53	0

The values of the coefficient in each region were determined based on the measured data within the X-axis range of 0.02–1. This means that the lower limit in Eq. (2) is 0.02. However, the data obtained in this study have a X-axis range 0.00057–0.0047, which is beyond the region in which Eq. (2) holds. Then, to examine the applicability of Eq. (2), the data obtained in this study were extrapolated up to 0.0005 before being compared with the measured data, as shown in Fig. 3. The solid line indicates the original correlation and the dotted line, the extrapolated region.

An excellent agreement is observed, and therefore, Eq. (2) can be used to the predict the maximum temperature position in an inclined tunnel with natural ventilation. However, further studies are required for Eq. (2) to be usable for estimating the velocity of natural ventilation in a full-scale tunnel.

$$\frac{L}{H_d} F_r^{1/2} \left(\frac{b}{D_2} \right)^{1/2} = \alpha_2 \left[\frac{H^{3/2} / b^{1/2}}{A_f^{1/2}} F_r Q^{*(2\eta - 1)/5} \right]^{\beta_2} \tag{2}$$

Table 2. Values of coefficient for each region [8].

region	ΔT_{max}		α_2	β_2
I	< 250 K	-1/3	0.79	0.73
II	$250 - 550$ K	0	0.92	0.6
III	≥ 550 K	1/2	1.02	0.56

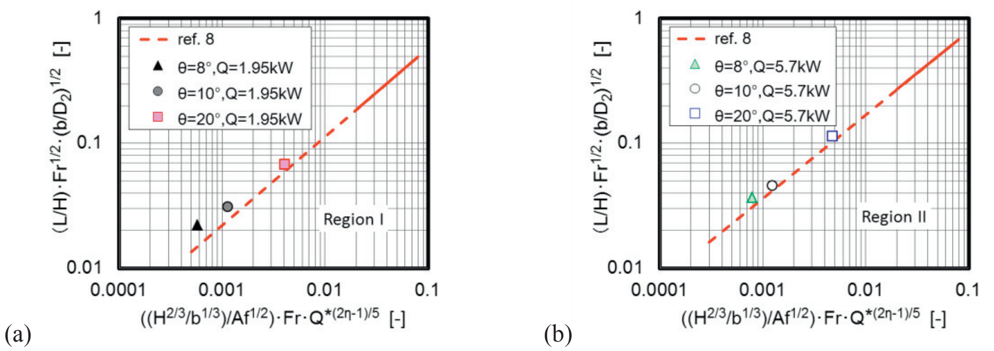


Fig. 3. Comparison between the predicted values and the experimental results of the maximum temperature position.

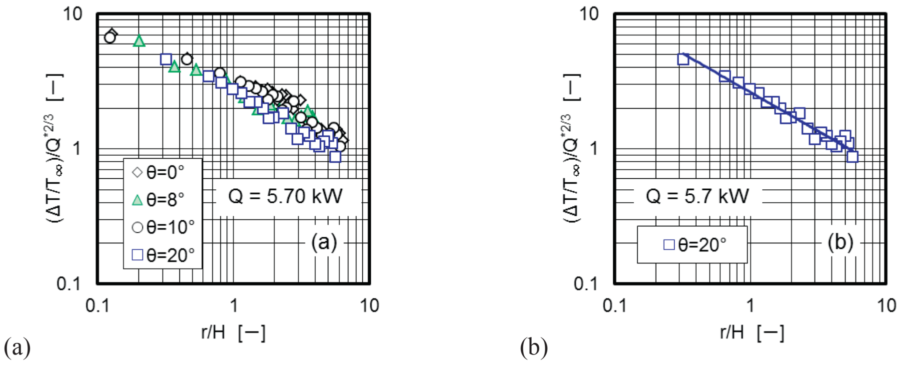


Fig. 4. Relationship between the normalized temperature rise and the travelling distance.

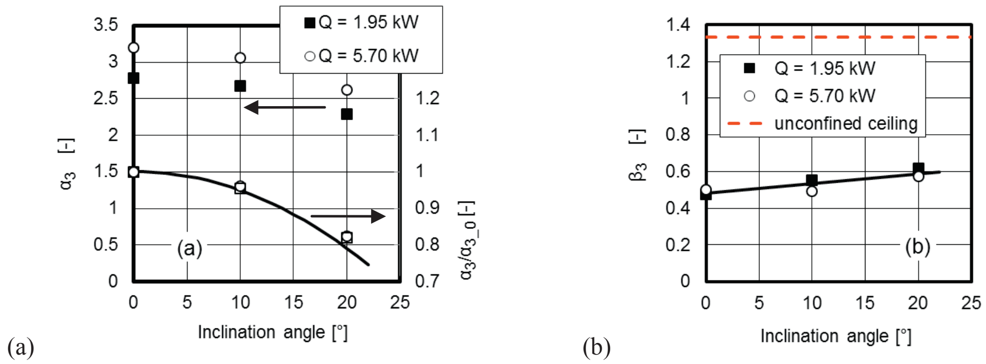


Fig. 5. Variation of coefficients, α_3 and β_3, against inclination angle.

3.2. Temperature along steepest run passing through ceiling centre in upward direction

Figure 4(a) shows the relationship between the normalized temperature rise and the travelling distance from the point at which the maximum temperature rise appeared along the steepest run in the upward direction. It is confirmed that the temperature decreased almost uniformly with the travelling distance for all inclination angles. To examine the influence of the inclination angle on the ceiling jet temperature, the power function was applied to the data measured at each inclination angle of the tunnel, as shown in Fig. 4(b), and the values of the intercept and power were estimated.

The estimated values of intercept, α_3, were plotted against the inclination angle of the ceiling as shown in Fig. 5(a) and the estimated values of the power are also shown in Fig. 5(b). Irrespective of the heat release rate, both values of α_3 gradually decreased with an increase in the inclination angle and showed at similar attenuation property against the inclination angle. Therefore, each α_3 value was normalized by the intercept value obtained for a horizontal ceiling, α_{3_0}, as shown in Fig. 5(a). The variation to the inclination angle for both Q = 1.5 kW and 5.7 kW corresponded very well. It is also confirmed that the value of the power, β_3, which shows the attenuation properties of the temperature, gradually increases with inclination angle as shown in Fig. 5(b). As the value of the power of the ceiling jet under an unconfined inclined ceiling is 4/3[18, 19], that in the tunnel is 1/2 or less. This phenomenon is due to the spread of the ceiling jet in being restricted in the spanwise direction by the sidewall and the decrease in the entrainment of the lower layer. This means that the hot layer spreads to quite a distance from the fire source.

Based on the limited experimental results obtained in this work, the following formulae were developed to describe the temperature of the ceiling jet that flows along the steepest run in the upward direction in an inclined tunnel.

$$
\begin{aligned}
&\left(\Delta T / T_\infty\right)/Q^{*2/3} = \alpha_3 \left(r/H\right)^{-\beta_3} \\
&\alpha_3 = A(-5.397\times10^{-4}\theta^2 + 3.606\times10^{-4}\theta + 1.000), \quad A = 2.785(Q = 1.95\,\mathrm{kW}),\ 3.203(Q = 5.7\,\mathrm{kW}) \qquad (3) \\
&\beta_3 = 5.323\times10^{-3}\theta + 4.820\times10^{-1}
\end{aligned}
$$

3.3. Gaussian thermal thickness

L_t denotes the Gaussian thermal thickness, which is defined as the distance from the point where the temperature becomes 1/*e* of the maximum temperature rise to ceiling surface without applying the *N*-percentage rule [20]. It has been reported that the thickness of the ceiling jet that flows under an unconfined horizontal ceiling is ~11% of the ceiling height [17], and that this thickness gradually increases with the increase of the inclination angle of the ceiling [18].

Irrespective of the heat release rate, the Gaussian thermal thickness in a horizontal tunnel corresponds to each other as shown in Fig. 6(a), and it is approximately 2.3 times thicker than a ceiling jet that flows under an unconfined horizontal ceiling as shown in Fig. 6(b).

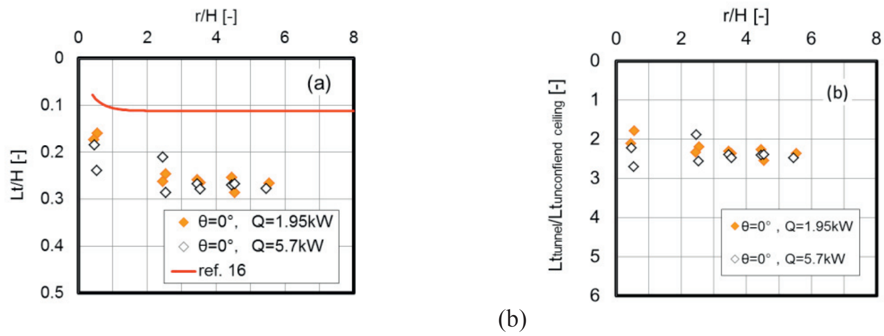


Fig. 6. Ceiling jet thickness in horizontal tunnel.

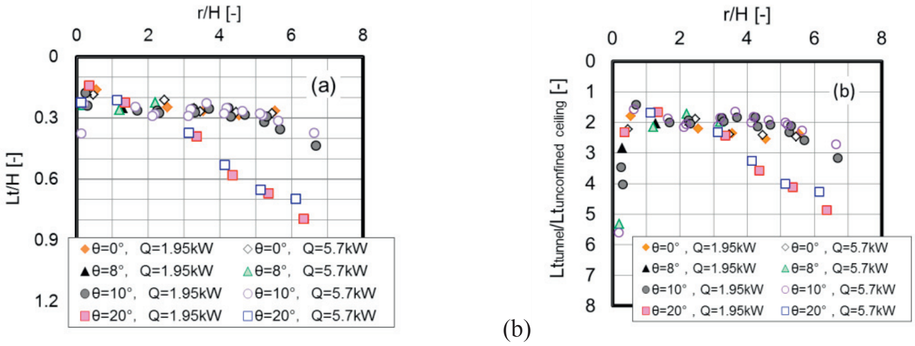


Fig. 7. Ceiling jet thickness in inclined tunnel.

As shown in Fig. 7(a), there is a branching point at which the ceiling jet thickness changes from the region in which it shows an almost constant value to the region in which its thickness increases with the travelling distance from the fire source; furthermore, this point gradually approaches the fire source with an increase in the inclination angle. It is thought that the properties of the flow along the inclined tunnel ceiling are different because the temperature distributions within the ceiling jet of θ=8° and θ=20° show different shapes. Moreover, the flow properties did not change suddenly at θ=20° and they are expected to change gradually depending on the inclination angle of the tunnel. A reasonable explanation is that the high performance of the thermal insulation of the model tunnel influences the data and the results up to θ=10° almost matched. Future studies will be required to understand the influence of the inclination angle on this change point.

At other inclination angles and heat release rates, the thickness of the ceiling jet in the tunnel became almost two times thicker than that under an unconfined ceiling. In particular, the increase in thickness at an angle of 20° is quite remarkable, as shown in Fig. 7(b). The increase in the thickness of the ceiling jet is considered to depend on the increase in the amount of mass flow rate along the tunnel axis that is caused by the spread of the ceiling jet being restricted in the spanwise direction by the sidewall of the tunnel.

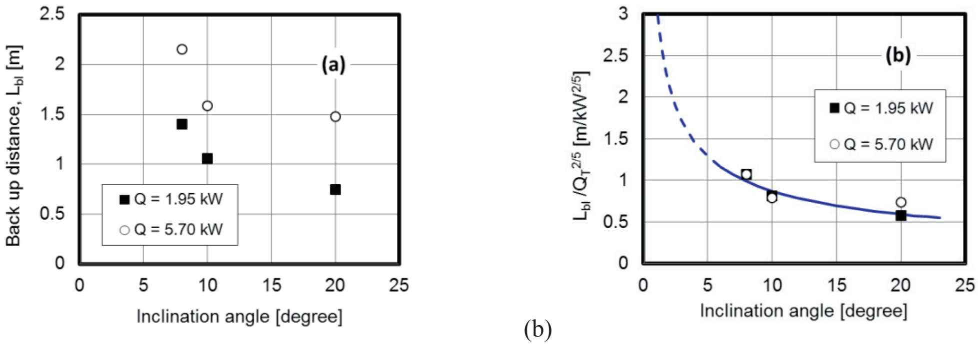
3.4. Backing-up distance of smoke layer to air supply side

The head position of the backing-up smoke layer in the downward direction is decided as the point at which the temperature rise of the smoke layer decreases to 2 K, and L_{bl} is defined as the distance from this head position of the backing-up smoke layer to the fire source axis.

The relationship between the backing-up distance of the smoke layer and the inclination angle of the tunnel is shown in Fig. 8(a). The following two features are confirmed. One is that the backing-up distance of the smoke layer decreases with an increase in the inclination angle of the tunnel, and the other is that the backing-up distance increases with heat release rate. As shown in Fig. 8(b), the effect of the heat release rate decreases if the backing-up distance is normalised by $Q^{2/5}$, and the data can be matched closely by Eq. (4) below. The data for Q=1.95 kW and Q=5.70 kW overlap at θ=8° and θ=10°, respectively.

The complex flow generated by the orifice installed at the inlet opening to measure the volumetric flow rate might influence the properties of the backing-up layer. This influence will need be examined through a CFD analysis in the future.

$$\frac{L_{bl}}{Q^{2/5}} = 3.18 \times \theta^{-0.562} \tag{4}$$



(a) (b)

Fig. 8. Backing-up layer distance.

4. Conclusions

In this study, we carried out a series of experiments of ceiling jets in an inclined tunnel. We have derived the following conclusions from our results.

1) A new correlation for predicting the maximum temperature rise of the ceiling jet in an inclined tunnel was developed based on a horizontal tunnel with longitudinal ventilation.

2) It is confirmed that the correlation for predicting the maximum temperature position in a horizontal tunnel with longitudinal ventilation can be applied to an inclined tunnel.

3) The ceiling jet thickness in a horizontal tunnel is approximately 2.3 times thicker than that under an unconfined horizontal ceiling. In addition, the ceiling jet thickness in an inclined tunnel is approximately two times thicker than that under an unconfined ceiling for the same inclination angle.

4) The ceiling jet temperature in a tunnel is higher than that under an unconfined ceiling for the same inclination angle. The value at which the dependence of the temperature attenuation against the travelling distance from the point at which the maximum temperature rise appeared along the steepest run in an upward direction increased with the inclination angle of a tunnel. However, this value is 1/2 or less of the ceiling jet that flows under an unconfined ceiling. An empirical formula for describing the temperature of the ceiling jet that flows along the steepest run in an upward direction in an inclined tunnel is developed.

5) A new correlation to describe the backing-up distance of a ceiling jet in the downward direction in an inclined tunnel is developed as a function of the inclination angle.

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