Friction-induced heat generation between two particles

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Abstract. Friction-induced heat generation, dissipation and the associated rise in temperature are still an intrinsic problem in many fields dealing with granular materials. This work presents preliminary attempts of modelling heat generation and estimating the contact flash temperatures with the use of a theoretical model. To check the robustness of this theoretical model simulations were run in parallel with Finite element method. The maximum contact temperatures obtained from the theoretical model show a good agreement with FEM results. The promising results imply that the simple theoretical model can be used accurately to predict heat generation in granular materials.

1 Introduction

The wide use of granular materials in human activities has proved an important literary genre in scientific community. Researchers have engaged a considerable amount of effort in understanding the complex physical behaviours of this ubiquitous material.

Despite the far-reaching research, the area of self-heating in granular media as a consequence of frictional interactions at the grain level remains largely not understood. It has been suggested that thermal conditions have a significant influence on the mechanical behaviour of a granular media, and because of that the questions like 1) how the heat is generated from friction 2) where it is dissipated and 3) how the associated rise in temperature is estimated, have become even more important.

When two bodies in contact are subjected to a relative tangential motion, frictional energy is said to be expended within their contact interface. The majority of the frictional energy is converted to frictional heat [1, 2], which in turn causes a rise in temperature especially in the vicinity of the contact. This temperature is also known as *contact temperature*.

In principle the contact temperature is a combination of three forms of temperatures; the bulk temperature, the ambient temperature and the flash temperature [3, 4]. *Bulk temperature* is the temperature averaged over the whole body, *Ambient temperature* is the temperature of the surroundings, it is usually considered constant while *Flash temperature* is the temperature localised over the area of contact.

The concept of flash temperature depicts the discrete nature of frictional contacts and thus it is directly linked to frictional heat. This concept was firstly brought forth by Block [5], but it took a couple of decades before industrialists recognised it to be a constricting factor for machinery efficiency. After gradually gaining importance, especially in the field of wear and lubrication, researchers attempted to measure flash temperatures of machines whose parts were susceptible to scuffing, this went across from cutting tools [6–8] to braking in rail-wheel systems [9–13].

Unlike the other types of temperature (bulk and ambient), the flash temperature is difficult to measure directly. Different experimental techniques have been applied to measure contact (or explicitly flash) temperatures but their level of accuracy is still limited. This is because the flash temperatures have a short life span (usually $10^{-3}s$ or less [14]) and a contact zone that is usually small and not easily accessible. Such difficulties made researchers to rely alternatively on the analytical techniques to determine the flash temperatures.

The widely used analytical approach is what is referred to as the *Plane heat source* method. This method is based on the assumption of a heat source placed on a surface of a body whose size is infinitely large compared to that of the heat source. Using this approach Jaeger and Carslaw [15] performed the mathematical modelling of the temperature distribution on a body due to instantaneous point source and line source placed on its surface. Similarly, Jaeger [16] and Block [17] derived analytical solutions for a moving heat source (an analogy to the case of friction), which were subsequently modified to relax some of the strict assumptions and approach more realistic cases [18–20]. Recently Tian and Kennedy [21] developed an approximate closed-form solution to predict both average and maximum contact temperatures for the entire range of sliding velocity.

Unlike other analytical models, the model from Tian and Kennedy [21] (referred to as TK model in this work) is distinguished for its mathematical simplicity, its validity for the entire range of sliding velocity and its ability to take into account the nature of contact. Eqs 1 and 2 show the solution for maximum contact flash temperature for elastic

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and plastic contacts, respectively.

$$T_{\max} = \frac{1.31 \mu p_0 V a}{\left[\lambda_1 \sqrt{(1.2344 + P_{e1})} + \lambda_2 \sqrt{1.2344 + P_{e2}} \right]}, \quad (1)$$

$$T_{\max} = \frac{2 \mu p_0 V a}{\sqrt{\pi} \left[\lambda_1 \sqrt{(1.273 + P_{e1})} + \lambda_2 \sqrt{1.273 + P_{e2}} \right]}, \quad (2)$$

where, T_{max} is the maximum temperature raise at the contact zone, μ is the coefficient of friction, p_0 is the mean contact pressure, V is the sliding velocity, a is the radius of contact area, λ is thermal conductivity, Pe is the Peclet number (i.e. a dimensionless term accounting for velocity) and subscripts 1 and 2 represent body 1 and body 2 respectively.

Finite element methods were also used mostly to solve Fourier's equations of heat conduction and predict the temperature distribution in both the stationary and moving members in transient and quasi-static conditions [22, 23]. However, in most studies, the treatment of thermal boundary at the interface creates thermal discontinuity. To curb this problem, a third body has to be introduced. Some researchers assumed the formation of debris at the interface and used discrete element methods to model the friction heat at the interface [24]. Furthermore, discrete element method was also used to model the frictional heat in grains placed between shearing walls [25–27]. However, the model used in the mentioned works employed the heat equation to estimate the bulk temperature of a particle thus ignored the local sharp temperature rise (flash temperatures) at contact points, which is often higher than the bulk temperature. Additionally, the validation of this model was based on an experiment that involved an external heat source, consequently, it was difficult to evaluate the robustness of the model at predicting the individual effects of frictional heat. Therefore, this work will look into frictional mechanisms between two particles in contact.

2 Methods

It was inferred from the previous section that, some theoretical models, particularly the TK model [21] can accurately estimate the contact temperature. The TK model also possesses some advantages over the other theoretical models in terms of mathematical simplicity and inclusiveness of contact parameters and the range of sliding velocity. However, before adapting such a model to numerical methods, it is essential to weigh its effectiveness in capturing maximum contact temperatures at varied input parameters.

The finite element method was resolved to be the best option for the preliminary validation of the theoretical model. The choice of FEM was based on the fact that it allows the study to focus on the local contact zone, which at this stage is more important than the whole body. In addition, FEM permits us to accurately model the thermal stresses caused by friction and capture the maximum nodal temperatures, which can be equivalent to the maximum flash temperatures suggested by the TK model.

The simulations of friction-induced heat generation between two spherical particles were performed in both the TK and the FEM models. The radii of both particles were set to be 100 μm, normal load, F ranging from $0.01-0.1$ N and sliding velocity, V from $0.1-1$ m/s. Also, the coefficient of friction, μ and thermal conductivity, λ were varied in the ranges of $0.1-0.5$ and $5-100$ W/mK, respectively. Other parameters were kept constant throughout the simulation i.e Young's modulus and Poisson's ratio were respectively $210,000$ MPa and 0.3, the yield strength was 600 MPa, the density was $7,850$ kg/m^3 and the specific heat capacity was 460 J/kgK. It is worth noting that, at this stage, the range of sliding velocities was limited to maintain a low value of Peclet number (below 2), this was done in order to avoid the problems of numerical oscillations which may rise when such models with high Peclet numbers are implemented in FEM [23].

For the theoretical (TK) model, the solutions highlighted in Eqs. 1 and 2 were written in MATLAB code and used to predict the maximum raise in contact temperature. It should be pointed out that in this model, the contact was assumed to be elastic and therefore, the Hertz theory was employed to estimate the contact parameters.

In the current FEM modelling, it was assumed that all frictional work is converted to heat which is distributed equally to the two contacting particles. One particle was kept stationary and the other was mobile, a constant normal load is then applied to the mobile particle that is moving towards the stationary one. Under a constant normal load, the contact area reaches a constant value, which is used to estimate the maximum contact temperature.

A commercial FEM solver ABAQUS/Explicit was used for the FEM modelling. In order to reduce the computational time, the symmetry boundary condition is applied where only one half of the set up is simulated. The hemispherical particle was meshed with 6,561 thermally coupled 3D elements (7,708 nodes) with a finer mesh around the contact zone (see Fig. 1).
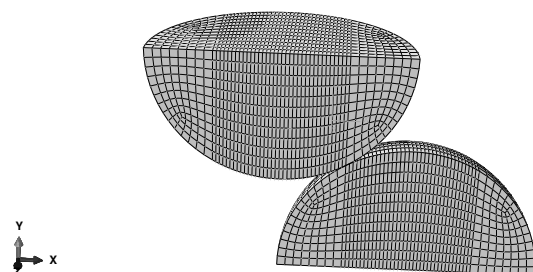

Figure 1. FEM model for two particles.

3 Results and Discussion

The results for maximum contact temperature estimated from the the described theoretical model as well as the FEM model are presented for a variety of parameters including normal applied force, sliding velocity, coefficient

of friction and thermal conductivity. This section will evaluate both the efficacy of the theoretical model in predicting the maximum contact temperature and the influence of these parameters on the trend of the resulting maximum temperatures.

3.1 Influence of applied normal load

The applied normal load was increased from 0.01 N to 0.1 N while the other parameters were kept constant i.e. the sliding velocity, $V = 1$ m/s, the coefficient of friction, the $\mu = 0.25$ and thermal conductivity $\lambda = 50$ W/mK. Fig 2 shows the resulting temperature at various normal loads. It can be deducted that the TK model give agreeable results with the FEM model, especially for low values of applied normal load. The values tend to differ at an increased normal load, this is because at these high normal loads the FEM model starts to develop regions of plastic deformation changing the contact conditions, whereas in the theoretical model only elastic deformations were assumed.
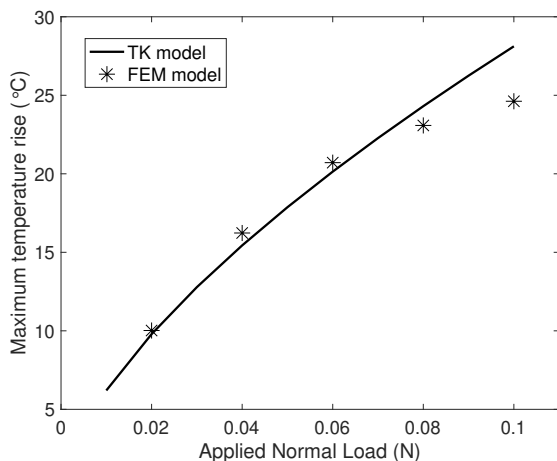
Figure 2. Maximum temperatures estimated from the theoretical (TK) model and the FEM model at various applied normal loads.

3.2 Influence of coefficient of friction

Another important parameter that affects the the amount of frictional heat is the coefficient of friction. Fig 3 presents the results of maximum temperature where coefficient of friction was varied and other parameters were kept constant i.e. the normal load, $F = 0.06$ N, the sliding velocity, $V = 0.5$ m/s and the thermal conductivity, $\lambda = 50$ W/mK. From the result, it is clear that TK model and FEM model are in good agreement, moreover they both show a linear relationship between the coefficient of friction and the temperature rise due to frictional heat.

3.3 Influence of sliding velocity

Sliding velocity is an important parameter that governs both the amount of generated heat and the severity of its penetration in the bulk of the material from the surface. To check how accurate the theoretical model is, the sliding velocity was varied between 0.1-1 m/s and other parameters were kept constant i.e. the normal load, $F = 0.02$ N,
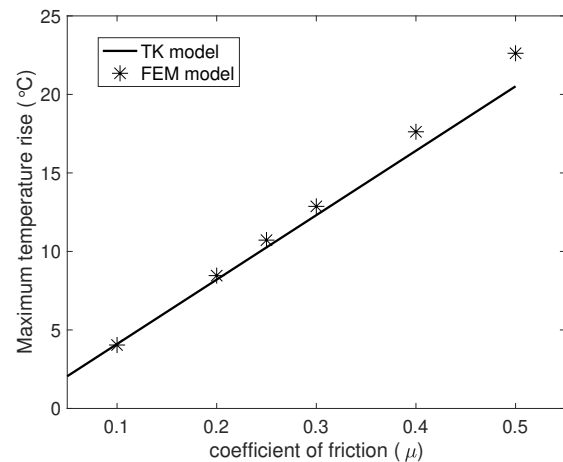
Figure 3. Maximum temperatures estimated from the theoretical (TK) model and the FEM model at different values of coefficient of friction.

the coefficient of friction, $\mu = 0.25$ and the thermal conductivity $\lambda = 50$ W/mK. Fig 4 presents the results where both theoretical model and FEM model are in good agreement. It should be noted that, in this case, the velocity is expressed in Peclet numbers (i.e. $Pe = \frac{Va}{2\kappa}$) in which the velocity, V was varied while the contact radius, a, and the thermal diffusivity, κ, were constant.
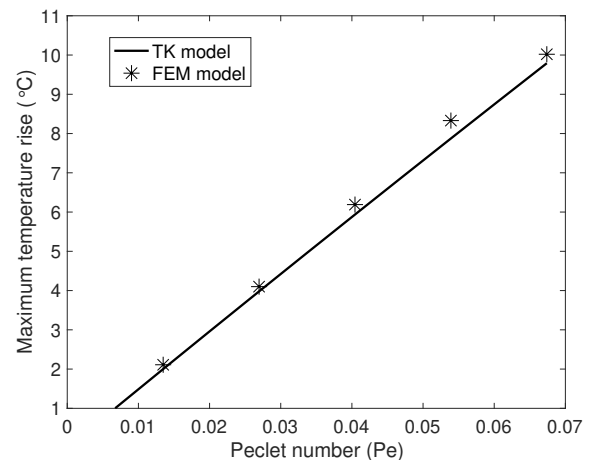
Figure 4. Maximum temperatures estimated from the theoretical (TK) model and the FEM model at different values of Peclet number (sliding velocity).

3.4 Influence of thermal conductivity

Thermal conductivity is directly related to how the generated heat translates to the rise of temperature. From the theoretical model, this parameter is not directly proportional to the resulting temperature and it has been observed that some models i.e Bowden model [28] could not predict the accurate temperatures at varied thermal conductivity. In this simulation, other parameters were kept constant i.e. the normal load, $F = 0.06N$, the coefficient of friction, $\mu = 0.25$, the sliding velocity, $V = 0.5m/s$ while the thermal conductivity was varied between $\lambda = 5 - 100W/mK$. The results of the maximum temperature are presented in Fig 5. It is shown that in both the TK model and the FEM model, the maximum rise in contact temperature reduces

with the increase of thermal conductivity. At low values of thermal conductivity the generated heat does not get transferred quickly to the bulk of the body resulting to very high temperatures on the surface, especially at the contact. On the other hand, at elevated values of thermal conductivity the generated heat is quickly to the bulk of the body, thus causing lower temperature rise on the contact surface. The results in this case show that the TK model is not only capable of giving the right trend for the temperature, it is also in accurate agreement with the FEM model.
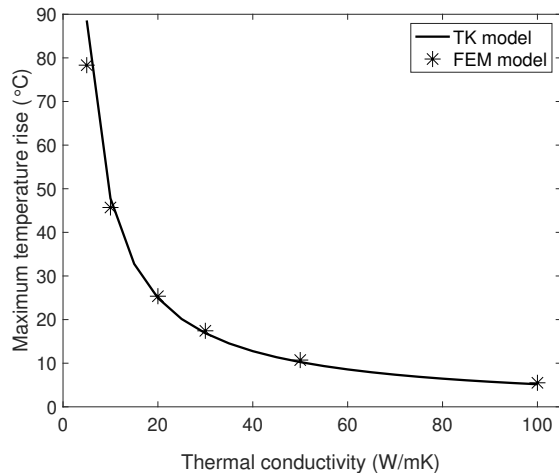

Figure 5. Maximum temperatures estimated from the theoretical (TK) model and the FEM model at different values of thermal conductivity.

3.5 Summary and conclusions

In this study the theoretical model (TK model) was evaluated and its ability to capture the heat generation and translate it into the temperature increase, especially in the contact zone, was analysed. The parametric study of the TK model has shown to be generally in good agreement with the FEM model for analysing the same heat generation problem. Despite its simplicity, the theoretical model comes with the cost of making general assumptions in estimating the contact parameters. This in turn may have impacted its accuracy in predicting the heat energy and temperature rise at extreme conditions, e.g. high normal loads and larger values of coefficient of friction.

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