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Collisions between particles in multiphase flows: Focus on contact mechanics and heat conduction

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A B S T R A C T

The topic of heat transfer between colliding particles or between particles impinging on solid surfaces is, in spite of its practical significance, still not widely studied in literature: efforts have, till now, led to only a handful of models. At the same time this problem is crucial not only for many types of multiphase flows but also for other systems involving colliding bodies. Therefore the first objective of the research was to study heat conduction between colliding particles for the case when the local deformation in the contact region can be treated as consisting of two regions: one deformating elastically and the other plastically. This requires investigation of collision dynamics and therefore this paper also contains a short review of the existing models for modelling particle–particle and particle–wall collisions. The second important result of the work presented here is a new relation for the coefficient of restitution that was developed by fitting a dimensionless relation involving the salient physical parameters to numerical experiments based on collision models.

1. Introduction

In many applications involving multiphase flow the effect of particle–particle and particle–wall collisions is important. This is especially true for relatively dense flows. Studying collisions is of interest both for practical aspects and for scientific curiosity. Particle–particle interactions have been widely studied in literature and various models have been proposed ranging from very fundamental ones, such as soft-sphere models, to more practical, such as the relatively simple models used in Eulerian approaches, and finally to purely empirical expressions.

Applications where heat transfer in fluid–solid flows is crucial include those that involve combustion. In such applications the heat transfer may be significantly affected by the presence of particles, for example, in dense fluidized beds and even, some researchers claim, in liquid-nanoparticles systems (nanofluids).

When two solid particles of different temperature approach each other they begin to exchange heat due to convection, conduction and radiation. During any contact heat conduction through the particle material plays the dominating role and the total heat transfer depends on the contact duration as well as their contact area. This mechanism for heat transfer in the system is more significant for systems involving particles made of materials of relatively high thermal conductivity and for systems with frequent particle–particle collisions. Heat conduction during contact is the focus of this paper, and to model it a description of impact dynamics is necessary.

Another thermal effect in systems involving colliding particles is the heat generated due to dissipative processes, such as friction and plastic deformation, during collisions. This is especially significant for contact-dominated flows, such as granular flows, and has already been researched for some time (see e.g., [1]). Nevertheless, for multiphase flows that are not contact-dominated, such heat generation can often be neglected.

1.1. Heat transfer between solid bodies during contact

The objective of this research is to focus on *heat conduction during contact* between particles or between a particle and a solid surface, such as a wall. A literature review relevant for this research is given in the paper by Sun and Chen [2] in which a model for heat conduction between colliding particles was also derived. Their model assumed the collision to be purely elastic and described by Hertz theory. More details are given in the following paragraphs.

Sun and Chen also performed experiments to investigate heat transfer effects associated with collisions (see [3]). This was done by studying a stream of particles impinging on a solid surface, which made it possible to assess the influence of a variety of parameters, such as particle velocity and amount of particles, on the heat transfer.

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Nomenclature

a	contact radius
b_1 and b_2	constant parameters
c_i	heat capacity
e	coefficient of restitution
E_*	effective Young's modulus
E_i	particle Young's modulus
$\vec{f}_p$	interphase force per unit volume
F	force acting on the particles during contact
k_i	heat conductivity
m_*	effective mass
m_i	particle mass
p	contact pressure
p_g	fluid pressure
Q	total heat transfer during collision
Q_e	total heat transfer during collision (only elastic deformation)
Q_p	total heat transfer during collision (only fully-plastic deformation)
q_w	heat flux
R_*	effective radius
$\bar{R}_*$	modified effective radius due to plastic deformation
R_i	particle radius
t	time
t_{coll}	collision duration
T_i	particle temperature
$\vec{u}_g$	fluid velocity vector
v_o	initial velocity along the normal direction
v_1	final velocity along the normal direction
Y	material yield stress

Greek symbols

δ	indentation
ΔT	initial temperature difference
ν_i	Poisson ratio
ν_g	fluid kinematic viscosity
ρ_i	particle density
ρ_p	fluid density

Subscripts

e	elastic
f	the end of collision
i	particle number ($i = 1, 2$)
m	average
max	the end of compression
p	transition between the elastic–plastic and fully plastic ranges
r	recovery period
J	model by Johnson
S	model by Stronge
y	transition between the elastic and elastic–plastic ranges

The model by Sun and Chen [2] has later been used by several other researchers for various applications. For example, Li and Mason [4] simulate a particulate flow with heat transfer effects using the discrete element method. They do not, however, use the Hertzian contact force and thus slightly modify the model by Sun and Chen in this respect. A similar strategy was used by the same group of researchers in subsequent works (see [5,6]).

The model by Sun and Chen has also been applied for e.g., bubbling fluidized beds with combustion (see [7]). Mansoori et al. [8] used the model of Sun and Chen for simulating turbulent flows with particles. The model has even been adopted for the Eulerian approach by Chang et al. [9]. Recently it has been revisited by Li et al. [10] who used an analytic solution of the mathematical model for heat conduction for any Fourier number.

Central assumptions in the model of Sun and Chen are that the contact surface between the particles is flat and that the heat transfer can be considered one-dimensional. Zhou et al. [11] improved the model by Sun and Chen by relaxing these assumptions to create a more realistic boundary between the particles. This was done by carrying out numerical simulations using the finite element method. New expressions were found that were later used also by Zhou and Yu [12,13]. According to Zhou et al. the original model by Sun and Chen yields similar results as using the more complex numerical simulations for low values of the Fourier number, as one might also suspect. When the Fourier number increases, the model by Sun and Chen overestimates the amount of transferred heat.

Some attempts have been made to account for other types of collisions, i.e., not only elastic. Ben-Ammar et al. [14] suggested an analytical model for plastic deformation for strain hardened metals. This model was validated experimentally by investigating particles colliding against a solid surface in vacuum so that the heat transfer between the bodies in contact was limited to conduction. This paper forms a basis for the present research as shown later in this paper. Also in earlier research by the present authors [15] a similar strategy was used for studying heat conduction for impacts with viscoelastic deformation.

Building on the work described above, the present paper describes a head-on collision of two non-rotating particles, where it is assumed with Sun and Chen that the collision process is relatively rapid so that the heat conduction between bodies is one-dimensional. It is further assumed that the surfaces are perfectly smooth so that there is no heat resistance at the boundary between the colliding bodies.

These assumptions limit the applications of the derived models somewhat but at the same time they make it possible to focus more on analytical or simple numerical techniques and thus avoid complex computer simulations during each collision. The results can be relevant for, among others, modelling of flows with many particles and frequent collisions.

1.2. Particle contact during collision

In order to investigate heat transfer during collisions the impact process has to be precisely described. One of the earliest and well-known is the paper by Cundall and Strack [16] who considered the particle–particle contact to be modelled by a spring–dashpot system. This strategy was later followed by numerous researchers, e.g., [17–19] (see also the review paper by Stevens and Hrenya [20]) who accounted for more realistic contact forces, or added other mechanisms such as cohesion between colliding particles, see e.g., [21].

An important issue that is highly relevant for the present research is plastic deformation of the colliding bodies. For some materials, such as steel, permanent, i.e., plastic, deformation in the point of contact takes place even for very low collision velocities. Therefore plastic deformation occurs frequently in systems involving this type of particles.