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論 文 内 容 の 要 旨

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論文題目　EVALUATION OF VARIOUS ESTIMATION EQUATIONS FOR PARTICLE-FLUID INTERACTION FORCES AND MODELING OF HEAT TRANSFER BETWEEN PARTICLES FOR DEM SIMULATIONS

The gas-solid two-phase flow takes a very important role in various industries such as medicine manufacturing, food processing, and combustion or gasification of coal.　Although these wide applications of the gas-solid two-phase flow have led to extensive researches, this phenomenon is very complicated and difficult to implement an experimental investigation of the flow characteristics.　On the other hand, not only the abilities of computers, but also the numerical algorithms to solve the phenomena coupled of fluid and particles have been developed.　As a result, numerical approaches have been introduced to design the powder processing industries.

The numerical simulations methods for two-phase flow are basically divided into three kinds of methods, which are the Two-Fluid Model (TFM), the Discrete Element Method (DEM) and Computational Fluid Dynamics (CFD) coupling model that is simply called as the DEM, and the Direct Numerical Simulation (DNS).　In the TFM, both gas phase and solid phase are treated as a fluid and solved by Eulerian method. The number of particles is not limited and it is also possible to analyze larger reactor relatively, as TFM can be incorporated into a lot of commercial code.　However, the particle adherence and the applicability to simulate various small scale phenomena in powder industry problem are difficult.

On the other hand, in the DEM-CFD coupling model.　The original DEM concept based was derived by Cundall and Strack in the field of geo-mechanics.　DEM was developed by Tsuji et al. by incorporating the CFD into the DEM. To distinguish the DEM from the original, they referred it as DEM + CFD model, but as write above, we will simply expressed it as DEM.　In the DEM, the motion of each particle is solved with Lagrangian method, and the motion equation for all particles needs to be solved.　Accordingly, the computational time of the DEM depends on the number of particles, and the computational load caused by the large number of particles sometimes brings serious problem.　In these two methods, some constitution equations for particle-gas interaction forces are also required. In addition, these two methods also cannot directly determine the small scale phenomena occurred around the particles such as drag, lift forces, viscous torque and also lubrication force.

In such small scale phenomena in fluidized bed, it would be a necessary to use other method such as the DNS. The DNS method does not basically require any constitution equations for the particle-gas interaction forces.　So far, various methods for the DNS have been derived, e.g. the finite element method (FEM), the boundary-fitted coordinates systems (BFC), the volume of fraction method (VOF), and the Immersed

Boundary Method (IBM).

In this research, a study has been done in order to incorporate the equations for small scale phenomena in particle fluid interaction forces such as, drag, lift force, viscous torque, and also the heat transfer between the contacting particles with DEM. In order to do that, we had utilized IBM that was proposed by Kajishima et. al. in our research. At first, in order to validate whether IBM can calculate small scale phenomena, a study to calculate lift force (Saffman force and Magnus force) and viscous torque of a particle in a various gas-solid two-phase flow systems has been done.

An examination of various estimation equations for drag force also has been done. In a DEM simulation, for drag force calculations, Wen and Yu equation is often used when the particles are dilute, while the Ergun equation is adopted when particles are dense. In a DEM simulation, these two equations are used interchangeably. However, there often exists a discontinuity between the two equations. In this sections, the drag force acting on both dilute and dense particle are also studied. In order to examine the effect of particle arrays and the relationship between the drag force and flow in a simple manner, particles were also arranged in a two–dimensional pattern.

In order to analyze the heat transfer in a fluidized bed using the DEM, we need to know (1) the particle-particle contact heat transfer, (2) the particle-gas heat transfer and (3) the particle-wall surface heat transfer. For the particle-gas heat transfer (2), Ranz and Marshall equations is often used. In the other hands, as for particle-particle contact heat transfer (1) and particle-wall surface heat transfer (3), Rong and Horio assumed a gas membrane between contact planes and calculated with the heat conduction equation, i.e. Fourier‘s law. However, the actual contact area i.e. the particle surface has surface roughness. Accordingly, the major problem in modeling the contact heat transfer model is how to consider the surface roughness on surface of particle. For the contact heat transfer between particles, the thermal contact resistance model was applied and the thermal resistance was modeled by placing a small solid block between the two contacting spheres in the simulation. In this research study, the applicability of this model was then examined by comparing with the experiments.

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KUWAGI Kenya, Bin ALIAS Azri, Bin MOKHTAR Muhammad Arif, TAKAMI Toshihiro

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Visualizations of flow in a fluidized bed by simulation and experiment
Azri bin Alias, Kenya Kuwagi, Yu Shimoyama, Toshihiro Takami, Hiroyuki Hirano

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接触二粒子に働く横方向力と粉体流動特性の関係に関する検討
Study on Effects of Geldart's Powder Classification on Lateral Force Using IB Method
Azri bin Alias, Kenya Kuwagi, Hiroyuki Hirano, Toshihiro Takami,

審査結果の要旨

流動層は粒子を充填した容器の底部から流体（多くの場合、気体）を吹き込み、粒子を流動化させた状態で様々な化学反応を行わせる化学装置である。流動層は発電用などのボイラー、ゴミ焼却炉など多くのプロセスで使用されている。コンピュータ性能の飛躍的な向上に伴い、流動層内の流動解析にも近年、数値シミュレーションが多用されるようになった。流動層のような固体と気体が混在するような固気二相流に対する数値シミュレーション法は主に３つに分けられる。気体とともに粒子も流体のように取り扱い、オイラー的に解析する二流体モデル(TFM)、気体はオイラー的に取り扱うのに対して、粒子は一つ一つ運動方程式を解き、ラグランジュ的に追跡していく離散要素法(DEM)、そして気体の計算メッシュを粒子サイズよりさらに小さく取り、粒子を固体壁として取り扱って、粒子サイズ以下の現象まで直接解く直接数値計算(DNS)である。TFM, DEM, DNSという順番で現象を精度良くシミュレーションすることができるが、コンピュータ負荷も飛躍的に増加していく。このような事情などから現在最も解析に用いられているのがDEMであると思われる。これはDEMが様々な紛体が関連するトラブル要素をシミュレーションに組み込むことができることにもよると考えられる。しかし、DEMは粒子スケール以下の現象を直接求めることができないため、そのような場合、何らかのモデル化の後、構成方程式をDEMの支配方程式に組み込んで解いていくことが必要になる。しかしながら、既存の構成方程式は多種多様な流動層内の現象をシミュレーションするのに十分とは言えない。そのため本研究では、DEMに組み込むことを目的とした構成方程式の検討を行っている。

本論文ではまず、粒子が流動化する最大の駆動力である粒子－流体間相互作用力に着目し、これまで提案されている推算式の精度を検討するため、DNSの一つである埋め込み境界法を用いてシミュレーションを行っている。粒子 - 流体間の相互作用力には様々なものがあるが、本論文では抗力、揚力、回転揚力、粘性トルクと様々なケースで検討を行っている。抗力に関しては長年使われてきているWen-Yu式、Ergun式とともに近年提案されたCelloらの式も比較を行い、空隙率、レイノルズ数、粒子配置などによりそれぞれ良好に一致する場合と、そうでない場合があることを見出している。

次に、温度場が問題となる場合に関して、粒子周りの伝熱について検討を行っている。この中で、粒子 - 粒子間接触伝熱に関してこれまでに良いモデル化がなされていないとして、接触熱抵抗と粒子間に微小な仮想固体を想定したモデル化を行って、そのモデルに基づくシミュレーションを行い、実験結果と比較している。その結果、粒子 - 粒子間接触伝熱は固定壁が完全に接触している場合と異なり、熱抵抗が存在していること、微小な仮想固体の物性値を調節することによりモデル化ができることを示している。

これらの結果は、流動層ばかりでなく紛体が関係する様々な工業プロセスに応用が期待でき、工業的に有意義なものと考えられる。

以上、本審査委員会は、本論文の審査ならびに公聴会における最終審査の結果に基づき、本論文は博士（工学）の学位に値するものと認める。