CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081109

Investigation of Moving Beds for Heat Recovery from Solid Granular

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Moving beds have been regarded as a promising alternative for the heat recovery from the gravity-driven granular flow, which includes counter-current moving bed (CCMB) and gravity-driven moving bed (GDMB). However, the heat transfer characteristics still deserve investigating to optimise the direct heat transfer (CCMB) and the indirect transfer (GDMB), particularly for the appropriate particle size in different moving beds. In this paper, the simple analytical models were established to compare CCMB and GDMB in different particle sizes, which was interwoven with the effects of solid granular density, thermal conductivity, the inlet temperature. It was found that, as the technology significantly affected by the solid-to-gas ratio of mass flow rate, CCMB enables the efficient heat recovery for the particles larger than 3 – 4 mm. For the other fine solid granular, GDMB becomes a good candidate once there is enough heat transfer area, fins in the airside and particles mixing in the granular side. It has more advantages in the quick flow with the compact design. The study can provide useful suggestions for improvement and optimisation in the future.

1. Introduction

Heat recovery from solid granular has attracted many attentions recently. Cheng et al. (2019) suggested that the moving bed was one of the promising candidates to recycle the huge waste heat in the metallurgy and building materials. Ho et al. (2018) explored that, the moving bed was useful in the Concentrate Solar Power (CSP) system, where solid granular was utilised as the energy medium. Compared with fluidised bed, moving bed has more advantages on less cost, manufacturability and transient operation etc. Moving bed can be classified into two types, i.e. counter-current moving bed (CCMB) and gravity-driven moving bed (GDMB). In CCMB, the cold air directly cools the hot granular along with the height so that the gas convection is the dominant heat transfer mechanism. The gas velocity, particles diameter as well as the bed height are the key factors affecting the heat transfer. Hadley et al. (2018) found that the appropriate solid-to-air ratio of mass flow rate locates around 0.8 - 1. Liang et al. (2019) explained the coupling effect between gas velocity, bed height and particle diameter. Usually, CCMB is more appropriate for large particles to avoid the high-pressure drop. As for GDMB, hot particles indirectly transfer heat to the working fluid through the wall. In the granular side, hot particles slowly flow around the wall with the driving of gravity. As a result, heat conduction and radiation are more vital, while gas convection can be ignored (Guo et al., 2019). The view is also adopted by Albert et al. (2019) in their theoretical analysis on particles physical parameters and geometry design in GDMB. Owing to the relatively small heat transfer rate in GDMB, enough heat transfer area is required. Jiang et al. (2019) optimised their GDMB with the double-system to balance the heat transfer area and efficiency. Generally, GDMB is more applied in the fine granular to overcome the difficulties in CCMB.
The critical particle diameter between CCMB and GDMB is the key factor for the optimisation in solid granular. In the past years, the critical diameter was only determined by the flow ability of air (Cheng et al., 2019), while seldom directly connected with the heat transfer performance. The selection of CCMB and GDMB were more dependent on the engineering experience. In the present work, the simple mathematical model was built to quickly compare the heat transfer recovery efficiency in CCMB and GDMB. The effect of air flow was would be considered in CCMB, and the thermal resistance theory (Sullivan and Sabersk, 1975) was adopted in prediction

Paper Received: 24/03/2020; Revised: 30/04/2020; Accepted: 24/04/2020
Please cite this article as: Guo Z., Tian X., Zhang S., Yang J., Wang Q., 2020, Investigation of Moving Beds for Heat Recovery from Solid Granular, Chemical Engineering Transactions, 81, 649-654 DOI:10.3303/CET2081109

of GDMB. Particularly, based on the thermal resistance theory, the potential of GDMB was quantitatively coupled with diameter, and the key characteristics were discussed for the improvement.

2. Mathematical descriptions for CCMB and GDMB

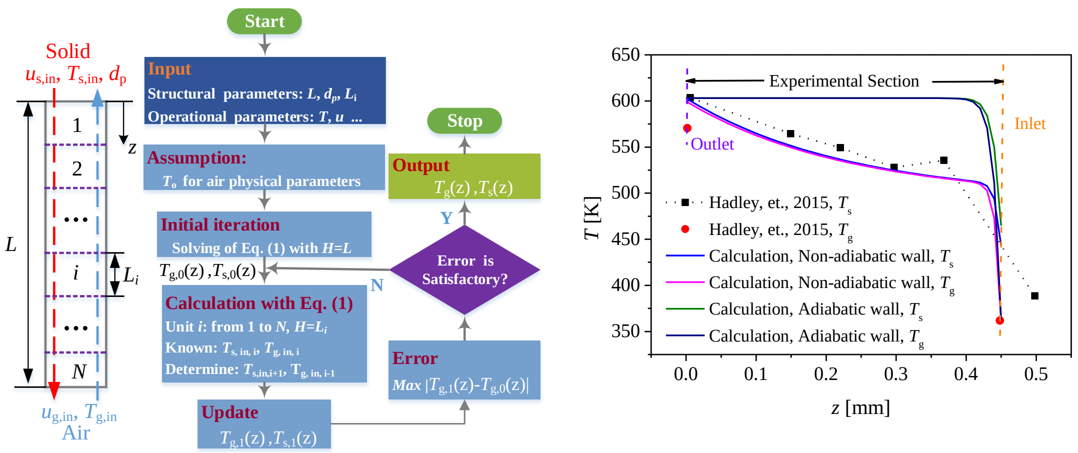
To evaluate the heat transfer in CCMB and GDMB, the analytical models are built.

2.1 Clarity Models for CCMB

CCMB is investigated by the 1-D model (Hadley et al., 2015), as shown in Eq(1). The heat transfer is dominated by convection between the air and the solid, as well as that between the air and the wall. The related heat transfer coefficients are calculable as the work of Hadley et al. (2015).

$$\begin{aligned} &\left(\rho c_{p}\right)_{s} u_{s} A_{\text{chanel, s}} \frac{dT_{s}}{dz} = h_{\text{s-g}} A_{\text{s-g}} \left(T_{g} - T_{s}\right), \quad z = 0 \;\; : \;\; T_{s} = T_{\text{s,in,i}} \\ &-\left(\rho c_{p}\right)_{g} u_{g} A_{\text{chanel, g}} \frac{dT_{g}}{dz} = h_{\text{s-g}} A_{\text{s-g}} \left(T_{s} - T_{g}\right) + h_{\text{g-w}} A_{\text{g-w}} \left(T_{w} - T_{g}\right) \quad z = H \;\; : \;\; T_{g} = T_{\text{g,in,i}} \end{aligned} \tag{1}$$

Because the air properties vary with the air temperature, the segmented method is applied in CCMB. As yield in Figure 1a, Eq(1) is solved to update the local temperature in each unit, where the air physical properties are determined by the results in the last cycle. After that, the overall temperature distribution can be quickly obtained with several iterations. This model is verified by the experimental data of Hadley et al. (2015), as illustrated in Figure 1b. Note that, the wall is non-adiabatic in the experiment. Combined with the boundary conditions provided by Hadley et al. (2015), the calculated solid temperature is well consistent with the measurement in the experimental section. The small deviations in the inlet and outlet are attributed to the additional heat loss in the experiment. As a whole, the model is credible in CCMB.



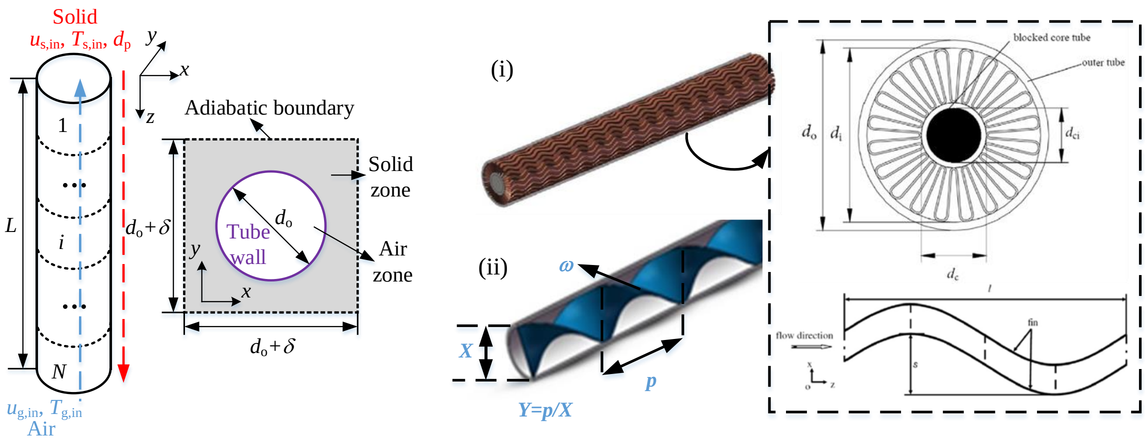
a: Flow chart of the overall solving process *b: Validation at $(\rho u)_s/(\rho u)_g$ =2.48*

Figure 1: A model establishment for counter-current moving bed (CCMB)

In particular, Figure 1b presents the calculation with the adiabatic wall. The heat transfer is completed in a narrow zone in comparison to that with the non- adiabatic wall. The solid temperature can increase by 21.6 K at z = 0.45 m without the heat loss through the wall, while the air temperature only rises by 3.4 K at z = 0. It can be concluded from Figure 1b that, the heat loss through the wall has a limited effect on the heat brought by the air, and $h_{g\text{-}w}$ = 0 can be adopted for the discussion in Section 3.

2.2 Models for GDMB

As depicted in Figure 2a, there are different channels for the air and the solid in GDMB. Heat transfer is developed through the tube wall, which worsens the contact between different phases compared with that in CCMB. To overcome the limitation, the larger scale is required in GDMB, and several fins should be adopted in the airside to, as displayed in Figure 2b. Table 1 lists the geometry size in the present study. Based on the parameters, the temperature distributions along the height are solved by the segmented Log-Mean Temperature Difference Method (Zhang et al., 2018). However, the heat transfer coefficient remains uncertainty in the granular side. According to Albert et al. (2019), it can be predicted by the heat resistance theory, which is firstly proposed by Sullivan and Sabersky (1975). As denoted in Eq(2), χ is an empirical parameter to determine the contact heat resistance, which is attributed to the void between particles and the tube wall. The latter part with the contact time (τ), represents the penetration heat resistance to reflect the degree of heat diffusion inside the granular flow. The larger τ corresponds to the thicker thickness of the temperature boundary layer, and heat transfer will be limited. It is determined by tube length and the granular flow rate. To enhance heat transfer in the granular side, the penetration resistance should be improved with small τ. It can be achieved by particles mixing between GDMB banks (Albrecht et al., 2019). In this work, several locations of mixing are regarded to homogeneously distribute along the tube and τ will become 0 once particles flow through each location. The effective thermal conductivity in Eq(2) is obtained by ZBS model (Zehner and Schlunder,1970), which considers both heat conduction and radiation inside the solid granular.



a: Geometry and boundary condition

b: Fins in the airside: (i) Wave-like type, z=0 to z=L/2, (ii) Twisted-tape-inserted type, z=L/2 to z=L. (Zhang et al., 2018)

Figure 2: Schematic of gravity-driven moving bed (GDMB)

Table 1: Tube size and fins size in GDMB

d_o /[mm]	d_i /[mm]	$d_{c,I}$ /[mm]	s /[mm]	l /[mm]	X /[mm]	Y /[-]	ω /[mm]
60	54	20	2	32	52	1.2	2

$$1/h = \chi d_p / k_g + 0.5\sqrt{\pi}\sqrt{\tau} / \left(\sqrt{\rho c_p k}\right)_{s,eff} \tag{2}$$

2.3 Comparison between CCMB and GDMB

The heat recovery efficiency (η) is defined as Eq(3) to compare the heat transfer in CCMB and GDMB. It is connected with the heat absorbed by the air (Q), the mass flow rate of the solid granular ($q_{m,s}$) and the temperature difference for the solid. By keeping the same solid granular, inlet temperature and mass flow rate, as summarized in Table 2, the characteristics of CCMB and GDMB are compared in different particle diameters. The height of GDMB is as twice as that of CCMB, which ensures enough heat transfer area for GDMB.

$$\eta = \frac{Q}{q_{m,s} c_{p,s} \left(T_{s,in} - T_{s,out}\right)} \tag{3}$$

Table 2: Main physical parameters and bed sizes in basic case (Solid granular refers to Hadley et al. (2015))

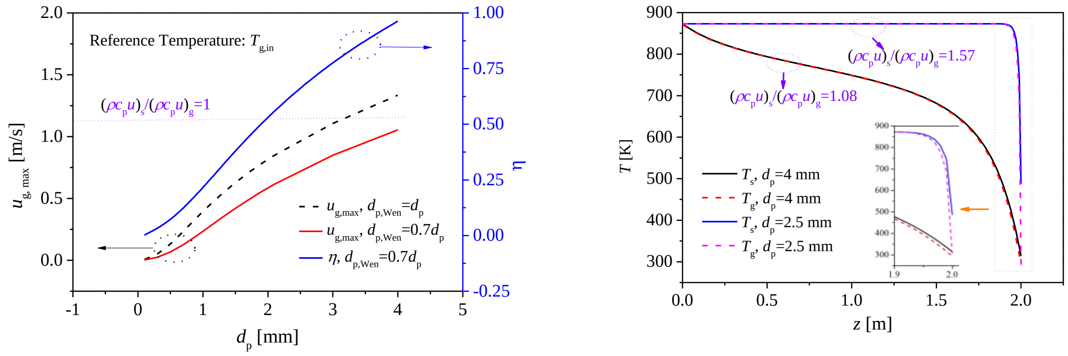
ρ_s /[kg/m^3]	$c_{p,s}$ /[J/(kg·K)]	k_s /[W/(m·K)]	Porosity	$T_{s,in}$ /[K]	$u_{s,in}$ /[mm/s]	L_{CCMB} /[m]	L_{GDMB} /[m]	δ /[mm]
3,100	880	1.55	0.453	873.15	1.0	2	4	40

3. Results and discussion

In this section, the characteristics of CCMB and GDBM are explored to discuss the critical diameter:

3.1 Characteristics in CCMB

To avoid the fluidisation in CCMB (Hadley et al., 2015), the maximum air velocity ($u_{g,\ max}$) should be under the minimum fluidised velocity, which is predicted by Wen and Yu correlation (Wen and Yu, 1966). The particle diameter ($d_{p,\ Wen}$) has significant effects on $u_{g,\ max}$, as shown in Figure 3a. The actual metallurgy and building materials contain particles in different sizes. Girimonte et al. (2019) reported that, between the mixing solid with the determined average diameter (d_p), there existed some smaller particles, of which the size even reaches the 70 % d_p. In consequences, the actual fluidised velocity is generally less than the value predicted by Wen and Yu correlation for the mixing particles (Pešic´et al., 2014). As discussed above, $d_{p,\ Wen}$ is equal to 70 % d_p to predict the $u_{g,\ max}$ in the study as follows.



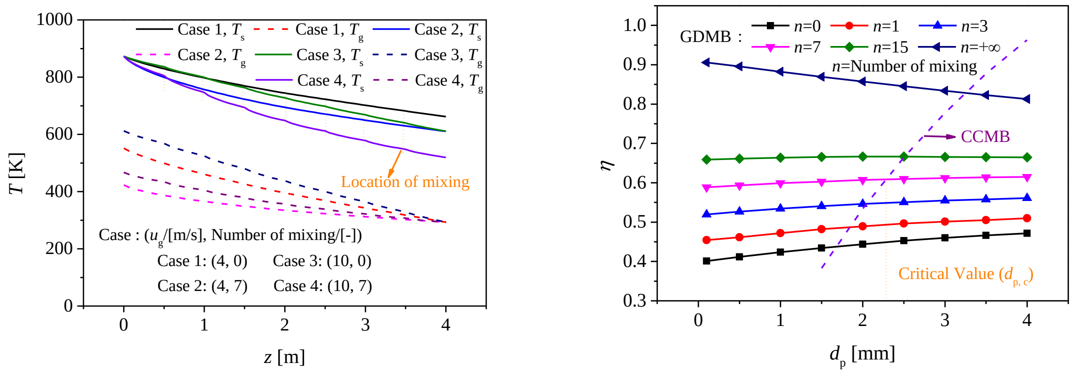
a: Max air velocity and heat recovery efficiency *b: Temperature distribution*

Figure 3: Results in counter-current moving bed (CCMB)

As illustrated in Figure 3a, η rapidly increases with d_p. Once d_p is smaller than 2 mm, η is lower than 50 %. In these cases, even though the air temperature can be heated to the inlet solid temperature, only a little overall heat (Q) is absorbed by the slow airflow. To achieve the satisfactory η (> 70 - 80 %), d_p should exceed 3 mm to broken the limitation of air velocity. According to Hadley et al. (2015), the fit solid-to-gas ratio of mass flow rate locates between 0.8 and 1, and d_p should be even larger than 4 mm in Figure 3a. Figure 3b displays the detailed temperature distributions. Once the solid-to-gas ratio deviates from 1 (d_p = 2.5 mm), the heat transfer only happens in the small zone near the gas inlet (z = 2.0 m). In other words, the CCMB space is not efficiently utilised for the small air mass flow rate. But if the ratio becomes closer to 1 (d_p = 4 mm), the air is more uniformly heated along the z-direction. Above all, CCMB is not an optimal design for the fine solid granular (d_p < 3 mm) in the industrial applications. The analysis resembles the point of Jiang et al. (2009).

3.2 Characteristics in GDMB

Because the airflow rate is independent of d_p in GDMB, GDMB has an advantage over CCMB on the efficient heat transfer in the fine particles, but the outlet air temperature is lower owing to the relatively poor heat transfer rate in GDMB. The competition between the advantage and the disadvantage leads to a critical particle diameter to distinguish the ability of heat transfer between CCMB and GDMB. The detailed law is explored in Figure 4.



a: Temperature distribution (d_p= 2.5 mm) *b: Heat recovery efficiency ($u_{g,\ in}$ =10 m/s)*

Figure 4: Results in gravity-driven moving bed (GDMB)

As shown in Figure 4a, both the increase of air velocity and the adoption of particles mixing decrease the outlet solid temperature. Once u_g increases to 10 m/s and 7 locations of particles mixing are set, the outlet solid temperature in GDMB is even close to that in CCMB at d_p = 2.5 mm. It means that both the heat resistance in the airside and that in the granular side appear vital for the overall heat transfer. More detailed comparisons on η are conducted in Figure 4b. The η is less sensitive to d_p in GDBM so that GDMB has a potential to achieve the steady heat recovery for the industrial solid granular in a wide range, at least d_p < 4 mm. However, compared with the stronger heat transfer rate in CCMB, more optimisations are necessary to improve η in GDMB. Because the heat transfer enhancement has been widely studied in the airside, the emphasis of Figure 4b is placed on the particle mixing in the granular side.

If none of the particle mixings is adopted (n = 0), the η in GDMB is only larger than that in CCMB at d_p < 1.6 mm. To magnify the critical d_p, the particle mixings are useful to decrease the penetration resistance in GDMB. More particle mixings correspond to the stronger enhancement and η can increase by more than 20 %. However, with certain amounts of particle mixing (n < 15), η is still smaller than 70 % and the critical d_p do not exceed 3 mm. The penetration resistance still plays more roles than the contact resistance. Heat transfer is enhanced with d_p, by which radiation is stronger to strengthen the ability of heat diffusion. The tendency will be weakened with the smaller penetration resistance at the larger n. If an ideal extreme condition is considered with ignoring of penetration resistance (n = +∞), there is an inverse relationship between d_p and η, which is dominated by the contact resistance. The η even approaches the level of more than 80 %, but the critical d_p only exceeds 3 mm a little. Above all, GDMB is not appropriate for the larger particles (d_p > 3 mm) while a good alternative for the fine particles (d_p < 1.6 mm) in comparison to CCMB. For particles between 1.6 mm and 3 mm, GDMB still requires some improvement to become a better candidate. The heat transfer performance is highly dependent on the penetration resistance, which is significantly affected by locations of particles mixings.

3.3 Critical particle diameter under different conditions

The control variable analysis is conducted for the critical particle diameter ($d_{p,c}$), as shown in Table 3.

Table 3: Variable controlling in different cases in comparison to basic case in Table 2

Case	1	2	3	4	5	6	7	8	9	10
Varying variable	$T_{s,in}$ /[K]		$u_{s,in}$ /[mm/s]		ρ_s /[kg/m^3]		k_s /[W/(m·K)]		δ /[mm]	
Final value	673.15	1,073.15	0.5	2.0	2,000	4,200	0.75	3.0	25	60

To enhance η in GDBM, the inlet air velocity is selected as 10 m/s, and the amount of particle mixing is equal to 7. Figure 5 illustrates the comparison of $d_{p,c}$ under different conditions. The inlet solid temperature ($T_{s,in}$), the solid density (ρ_s) and the solid thermal conductivity (k_s) all have limited effects on $d_{p,c}$. Even though the heat flux (Q) is influenced by these variables, the similar trends cannot broaden the differences between CCMB and GDMB. By contrast, the solid velocity ($u_{s,in}$) and the channel width (δ) are the major factors affecting $d_{p,c}$ Both the increase of $u_{s,in}$ and the decrease of δ are only beneficial to improve Q in *GDMB.* The development of penetration resistance is overcome so that $d_{p,c}$ increases. Consequently, GDMB has more advantages for the faster granular flow combined with the compact design, which confirms to the analysis of Albert et al. (2019). However, the maximum $d_{p,c}$ is smaller than 3.5 mm in Figure 5, and GDMB is still not appropriate for particles in the large size. In particular, the large particles may be stagnated in the compact design so that the wider δ is necessary, which decreases $d_{p,c}$ on the contrary.

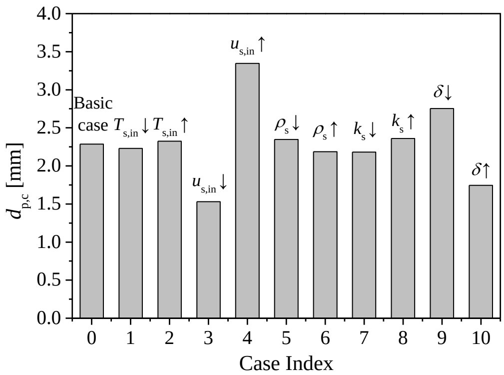


Figure 5: Critical particle diameter (dp,c) between CCMB and GDMB (ug, in=10 m/s, n=7)

4. Conclusions

In the present study, the heat recovery from the solid granular flow was investigated in the counter-current moving bed (CCMB) and the gravity-driven moving bed (GDMB). By the simple analytical algorithms, heat recovery efficiencies (η) were discussed in different particle diameters for each bed. The major findings are summarised as follows:

(i) CCMB has more advantages on the efficient heat transfer rate between the air and the solid due to the direct heat transfer. The heat transfer is highly dependent on the solid-to-gas ratio of mass flow rate, which should be close to 1. However, the air velocity in CCMB is limited by the particle size (d_p) to avoid the local fluidisation. In results, CCMB is more appropriate for the large particle (d_p > 3 - 4 mm) to achieve the satisfactory η.

(ii) GDMB is a promising alternative for the fine granular (d_p < 3 mm) with the relatively steady η. The way of indirect heat transfer makes the air velocity independent of d_p, but it also limits the heat transfer area between different phases. As a consequence, the large enough scale, the fins in the airside and the particle mixing in the granular side are all important to improve η in GDMB. In particular, appropriate particle mixings can significantly increase η by more than 20 % through weakening the penetration resistance.

However, the present work only discusses the basic characteristics of CCMB and GDMB. More detailed improvements for CCMB and GDMB can be coupled with the optimisation algorithm, such as particle swarm optimisation, in the future. The dynamic characteristics, including the effects of inlet temperature fluctuation or velocity fluctuation, can be also focused on.

Acknowledgements

The work is financially supported by National Basic Research Program of China (Grant No. 2017YFB0603500) and National Natural Science Foundation of China (No.51536007).

References

Albrecht K.J., Ho. C.K., 2019, Design and operating considerations for a shell-and-plate, moving packed bed, particle-to-sCO_2 heat exchanger, Solar Energy, 178, 331-340.

Cheng Z.L., Guo Z.G., Tan Z.T., Yang J., Wang Q.W., 2019, Waste heat recovery from high-temperature solid granular materials: Energy challenges and opportunities, Renewable and Sustainable Energy Reviews, 116, 109428.

Girimonte P., Vicacqua V., 2011, The expansion process of particle beds fluidised in the voids of a packing of coarse spheres, Powder Technology, 213, 63-69.

Guo Z.G., Tian X., Tan Z.T., Yang J., Wang Q.W., 2019, Optimisation of gravity-driven granular flow around the tube for heat transfer enhancement, Chemical Engineering Transactions, 76, 247-252.

Hadley T.D., Pan Y.H., Lim K.S., Orellana J., 2015, Engineering design of direct contact counter current moving bed heat exchangers, International Journal of Mineral Processing, 142, 91-100.

Ho. C.K., Carlson M., Albrecht K.J., Ma Z.W., Jeter S., Nguyen, M., 2018, Evaluation of alternative design for a high temperature particle-to SO_2 heat exchanger Proceedings of the ASME: 12th International Conference on Energy Sustainability, Lake Buena Vista, FL, USA, 7504.

Jiang B.F., Xia D.H., Guo H., Xiao L.S., Qu H.Y., Liu J.X., 2019, Efficient waste heat recovery system for high-temperature solid particles based on heat transfer enhancement, Applied Thermal Energy, 155, 166-174.

Liang X., Liu J.X., Xia D.H., 2019, Lagrangian simulation and exergy analysis for waste heat recovery from high-temperature particles using counter current moving beds, Applied Thermal Energy, 160, 114115.

Pešic´ R., Kaluderovic´ Radoicˇic T., Boškovic´-Vragolovic´ N., Arsenijevic´ Z., Grbavcˇic´, Z., 2014, Heat transfer between a packed bed and a larger immersed spherical particle, International Journal of Heat and Mass Transfer, 78, 130-136.

Sullivan W.N., Sabersk R.H., 1975, Heat transfer to flowing granular media, International Journal of Heat and Mass Transfer, 18, 1, 99-107.

Wen C.Y., Yu. Y.H., 1966, Mechanics of fluidisation, Chem. Eng. Prog. Symp. Ser., 62, 100-111.

Zehner P., Schlunder, E.U., 1970, Thermal conductivity of granular materials at moderate temperatures, Chem. Ing. Tech., 42, 933-941 (in German).

Zhang P., Ma T., Li W.D., Ma G.Y., Wang Q.W., 2018, Design and optimisation of a novel high temperature heat exchanger for waste heat cascade recovery from exhaust flue gases, Energy, 160, 3-18.