EDEM Contact Model:
Hertz-Mindlin with Liquid Bridge

Note this contact model uses the EDEM v2.2 API

Revision 2.2/2

Contents

Description of the model

The presence of moisture content leads to cohesion due to capillary forces. When liquid surfaces are nearby, a liquid bridge is created leading to an attractive force due to surface tension and the hydrostatic pressure inside the bridge. Moisture content also leads to the development of viscous forces which are secondary to the secondary effect of capillary forces in the case of low moisture content. The present Liquid Bridge model is used to model the effect of the capillary forces. This model does not take into account the effect of viscous force and is therefore only relevant for simulation of a system with low moisture content. This model has been written and validated by Brenda Remy et al.[i] (BR) for same size particles with same content of water (water ideally distributed).

Theory review

The model provided by BR is based on the liquid bridge force model developed by Mikami et al.[ii] The cohesion force due to the liquid bridge is a normal force acting between two particles that have been previously in contact and whose separation distance has not reached the rupture distance.
The cohesion force is expressed by:

$$\widehat{F_c} = \exp\left(A\hat{h} + B\right) + C$$

With A, B and C for particle – particle liquid bridge defined by:

$$A = -1.1\hat{V}^{-0.53}$$
$$B = \left(-0.34\ln\hat{V} - 0.96\right)\theta^2 - 0.019\ln\hat{V} + 0.48$$
$$C = 0.0042\ln\hat{V} + 0.0078$$

With A, B and C for particle – wall liquid bridge defined by:

$$A = -1.9\hat{V}^{-0.51}$$
$$B = \left(-0.016\ln\hat{V} - 0.76\right)\theta^2 - 0.012\ln\hat{V} + 1.2$$
$$C = 0.013\ln\hat{V} + 0.18$$

Where $\widehat{F_c}$ is the normalized capillary force $\widehat{F_c} = F_c/\pi R_{eff}\gamma$, γ is the surface tension of the liquid, $\hat{V}$ is dimensionless the liquid bridge volume ($\hat{V} = V/R_{eff}^3$), and $\hat{h}$ is the dimensionless separation distance between the surface of particles ($\hat{h} = h/R_{eff}$).
R_{eff}, the effective radius, is defined for particle – particle bridge according to the Derjaguin approximation[iii] as:

$$\frac{1}{R_{eff}} = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

And R_{eff} is equal to the radius of the particle for particle – wall liquid bridge. Note that in the case of same size particle of radius R, $R_{eff} = R$.

The liquid volume V is defined according to Shi and McCarthy[iv]:

$$V = V_1 + V_2$$

With $V_1 = \frac{L_1}{2} \times \left(1 - \sqrt{1 - \frac{R_1^2}{(R_1+R_2)^2}}\right)$ and V_2 defined similarly.

Utilization of the model

Setting the liquid content

The user must define the moisture content in the settings of the factory. The user needs to input in the “liquid content” parameter the mass percentage of liquid with regard to the mass of the particle to be “attached” to the particle to be created. An input of “5” means that the moisture content is 5 w%.

Setting the contact radius

Since the liquid bridge force acts when particles are not physically in contact, the liquid radius must be set bigger than bridge rupture distance. This is done by setting the Contact Radius in the EDEM Creator > Particles tab to be larger than the Physical Radius. The liquid bridge can then exist when the contact radii overlap even if there is no physical contact.

Rupture distance in the case of particle – particle liquid bridge:

$$\frac{s_{cp}}{r_{eff}} = (0.62\theta + 0.99)\left(\hat{V}\right)^{0.34}$$

Rupture distance in the case of particle – wall liquid bridge:

$$\frac{s_{cw}}{r} = (0.22\theta + 0.99)\left(\hat{V}\right)^{0.32}$$

Table 1: Particle-Particle bridge rupture distance scp/rp

Water content v%	Wetting angle					
	0	10	20	30	40	50
0.01%	0.036	0.039	0.043	0.047	0.051	0.055
0.10%	0.078	0.086	0.095	0.103	0.112	0.120
0.50%	0.134	0.149	0.164	0.178	0.193	0.208
1.00%	0.170	0.189	0.207	0.226	0.244	0.263
2.00%	0.215	0.239	0.262	0.286	0.309	0.333
4.00%	0.272	0.302	0.332	0.362	0.391	0.421

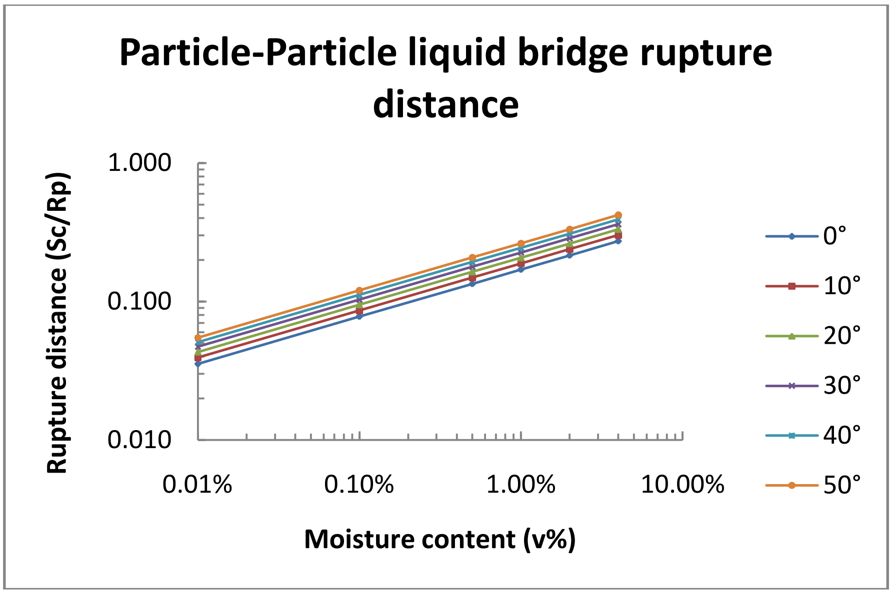
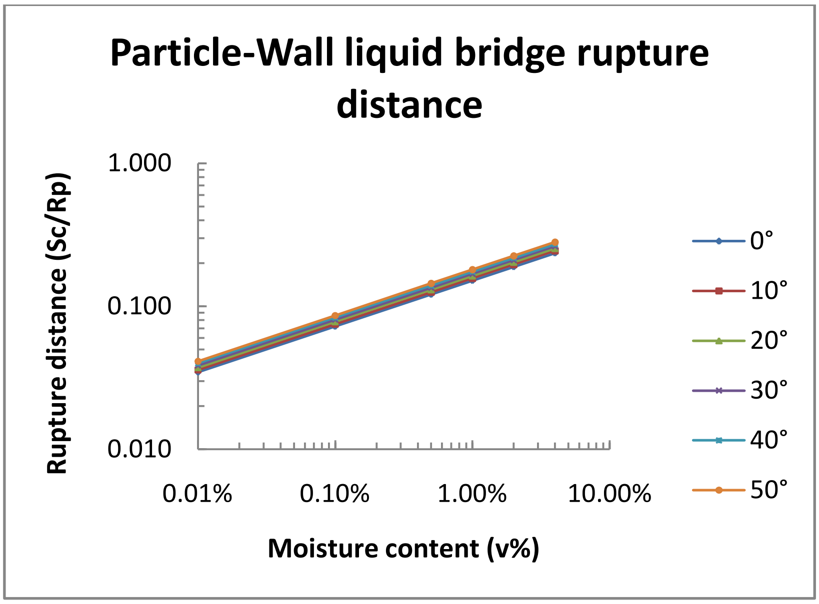


Table 2: Particle-Wall bridge rupture distance scw/rp

water content v%	Wetting angle					
	0	10	20	30	40	50
0.01%	0.035	0.036	0.037	0.039	0.040	0.041
0.10%	0.072	0.075	0.078	0.081	0.083	0.086
0.50%	0.121	0.126	0.130	0.135	0.140	0.144
1.00%	0.151	0.157	0.163	0.169	0.174	0.180
2.00%	0.189	0.196	0.203	0.210	0.218	0.225
4.00%	0.235	0.244	0.254	0.263	0.272	0.281



Validation of the model

This model has been experimentally validated by Brenda Remy et al.[i]. The original model was implemented in EDEM API v1.1 and has been updated by DEM Solutions to API v2.2 to allow for multi-processor support. A relative comparison of the same simulation performed with the model from Brenda Remy and the transcription of this model into API v2.2 has been done. The simulation test case is a mixer with granular material whose moisture content is 4.5 v%, therefore the contact radius was set to 1.3 physical radius.

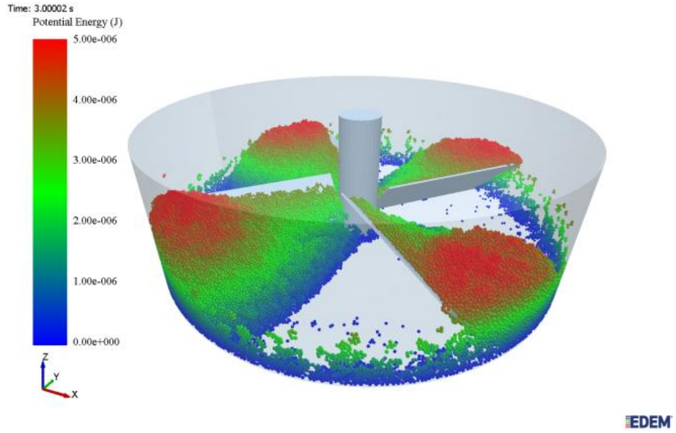


Figure 1: API v. 1.1 – 172k particles

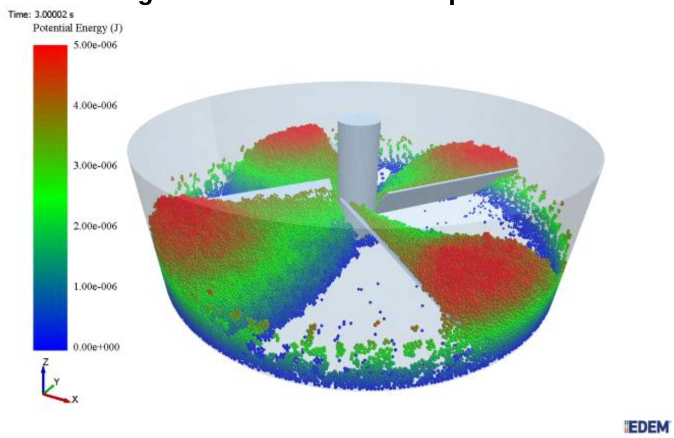


Figure 2: API v. 2.2 - 175k particles

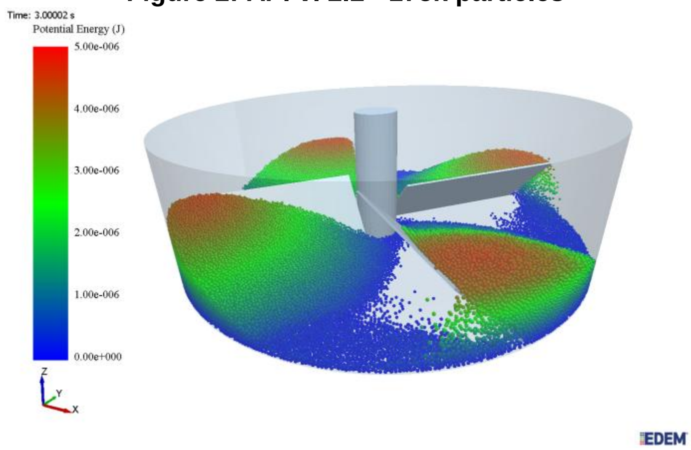


Figure 3: Hertz-Mindlin model – 172k particles

Figure 1 and Figure 2 show that the particles' behavior are in agreement, meaning that the transcription of the model into version 2.2 of the API did not introduce any errors.

One can see than compared to the simulation performed with Hertz-Mindlin model (c.f. Figure 3), particles stick to the wall, form agglomerates and the piles of particles pushed by the blades have a steeper slope.

Performance comparison

Simulation with the JKR model

The EDEM JKR model can also be used to model cohesion. A simulation test has been run to assess whether the JKR model can reproduce the same behavior as the Liquid Bridge model and also compare the time to perform the simulation.

After a small scale comparison of JKR inputs vs. Liquid Bridge inputs to determine the representative Energy Density for the JKR model which agrees with the Liquid Bridge Moisture Content inputs, a simulation with 175000 particles has been run with the JKR model. It globally shows a similar behavior with agglomerates, particles sticking to the wall of the mixer. However the particles seem to pile up more at the tip of the blades. These differences are attributed to the non-calibrated JKR inputs, but it shows that a similar behavior can be obtained with the JKR model.

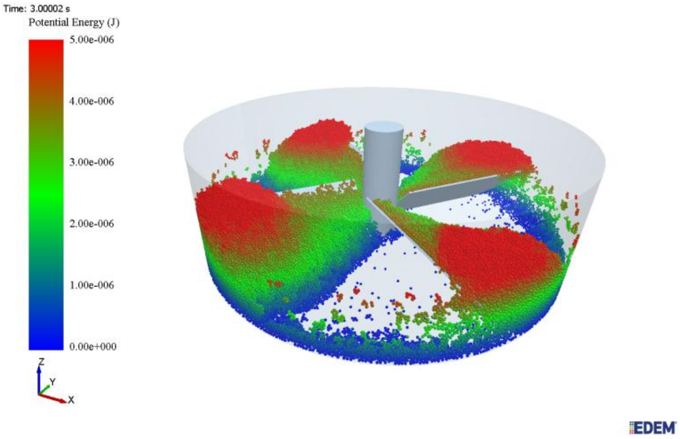


Figure 4: JKR model - 175k particles

Performance comparison

The simulation time of the simulation performed with the Hertz-Mindlin model, the JKR model and the Liquid Bridge model written in two different versions of the API is reported in Table 3.

Table 3: Performance comparison

Simulation name	Time (in hours)
HM - 172k	6
API 1.0 – 172k	70.4
API 2.2 – 175k	17.8
JKR – 175k	8

The Liquid Bridge model in API 2.2 is four times faster than in API v. 1.1. It really benefits from the multi-threading introduced with API 2.x. However it is about two times slower than the JKR model. One of the reason is that the liquid bridge model needs to use a contact radius bigger than the physical radius. Another reason is the use of particle and contact custom properties. A simulation with a lower moisture content and a smaller contact radius (1.1 physical radius) yields a slightly lower simulation time (15.4 hours with the API 2.2) but it is not as fast as the JKR built-in model.

Comments and suggestion of amelioration

The Liquid Bridge model has been developed to handle particle of different size however to experimental have confirmed the validity of this model for different size particles.

The Liquid Bridge model does not take into account the transfer of liquid content from particles to particles. Adding this capability to the model would allow the simulation of mixing between wet and dry particles which cannot be done by the JKR model.

Acknowledgements

DEM Solutions thanks Brenda Remy for sharing the liquid bridge model she developed for the version 1.1 of EDEM API and for her guidance in the transcription of this model into the version 2.2 of the API.

Bibliography

[i] Remy B, Khinast JG, Glasser BJ. Wet Granular Flows in a Bladed Mixer: Experiments and Simulations of Monodisperse Spheres. *AIChE J.* 2012; 58:3354–3369.
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