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TAPPING OF STRATIFIED LIQUIDS FROM A PACKED BED

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ABSTRACT

The problem of tapping of two immiscible liquids from a side slot is revisited. This study aims, in particular, at the metallurgical applications of the problem where the molten metal and slag are tapped from the coke-bed in the furnace hearth. CFD techniques have been employed in order to perform a systematic study of this problem and clarify the underlying physical mechanisms controlling the tapping behaviour. The influence of density and viscosity ratios as well as the packed-bed characteristics on the onset of entrainment of the lighter liquid into the taphole is studied. Buoyancy effects were found out to be the underlying parameter in determining the onset of the simultaneous tapping. In the absence of packed bed, the viscosity ratio was found out to have no influence on the tapping behaviour. With the presence of the packed-bed, however, the tapping behaviour is drastically changed. The onset of entrainment of the lighter liquid as well as the gas-liquid interface into the taphole is advanced, leading to the considerable amounts of the lighter liquid to be remained in the reservoir.

NOMENCLATURE

d diameter (m)
g gravitational acceleration (m/s²)
g' reduced gravitational acceleration (m/s²)
v superficial velocity (m/s)
C dimensionless function of porosity
Fr Froude number (-)
H,h heights (m)
L reservoir length (m)
P pressure (Pa)
Q flow rate (m^3/s), or (m^2/s)
S porous media resistance ($kg/m^2.s^2$)
α density ratio (-)
β viscosity ratio (-)
ε porosity (-)
κ permeability (m^2)
μ dynamic viscosity (kg/m.s)
ρ density (kg/m^3)
$\Delta\rho$ density difference (kg/m^3)

Subscripts

d taphole
cr critical
m heavier liquid (metal)
p particle
s lighter liquid (slag)

Superscripts

k phase

INTRODUCTION

Tapping is a common process in the metallurgical industries, which is the process of drainage of molten metal and slag from a side hole in the furnace. In the furnace hearth, the molten metal and slag layers segregate into two separate layers due to density difference. The viscosities of the two layers are also largely different; the molten slag is usually several orders of magnitude more viscous. In blast and smelting electric arc-furnaces, the hearth is often packed with coke particles, so that the liquids inside the hearth can only flow throughout the void space between the particles. Hence, the tapping process is often idealized as the drainage of immiscible liquids from a packed-bed reservoir. Throughout their pioneering experiments, Fukutake et al. (1976) showed that during the tapping period, the slag surface tilts towards the taphole resulting in an early discharge of the furnace gases and remaining of relatively large amounts of slag in the furnace. These observations were furthermore completed by Tanzil et al. (1986) where they showed that the slag/metal interface may also tilt towards or away from the taphole (Fig. 2), i.e., molten metal and slag are, in fact, expected to flow out simultaneously from the taphole. Simultaneous to the tapping of the overlaying slag layer, the metal layer is also entrained into the taphole from levels well below the level of taphole.

In fluid mechanics, the entrainment of immiscible liquids during the tapping of one or the other is a well-known phenomenon. In many applications, it is necessary to predict the maximum rate of withdrawal of a fluid with desired properties which can be attained before fluid from a different level also begins to flow (Turner, 1973). Craya (1949) and Huber (1960) considered various cases of point and line sinks in the end wall of a channel, at different levels from the interface between the two layers, and proposed methods for calculating the form of the interface as well as the critical condition for ‘drawdown’. Further improvements of the theory of the withdrawal from a two-layer fluid through a line sink were carried out (e.g., Tyvand, 1992, Hocking, 1995, and Stokes, et al., 2003). The fundamental difficulty, however, is in the validation of the theory with experimental results, as such experiments can never be really steady and there are always viscous effects at boundaries and interfaces (Wood, 2001).

The flow behaviour of tapping of immiscible liquids in industrial applications is far more complex. Tapholes have finite diameters comparable to the height of liquid layers in the system. Drainage rates as well as the viscosity of the working liquids are often quite high. As mentioned before, the flow to the tapping can also pass through a packed bed. The complex flow behaviour is, therefore a result of the simultaneous action of inertial, buoyancy and viscous forces, including the geometrical effects represented by the packed bed.

In this work, CFD techniques have been employed in order to perform a systematic study on this multi-variable problem. Parameters like density, viscosity and porosity are set to vary in relatively large ranges and parameter studies are performed in order to find out the degree of influence of each of these parameters on the tapping. Our major concern has been to cover as much as possible of the range of material properties relevant for metallurgical industries. The published results from various experiments and similar numerical simulations (e.g., Nishioka et al., 2003) are all confined to narrow ranges of density and viscosity ratios between the metal and slag layers.

THEORY

Figure 1 shows the 2-D geometry of the tapping system under consideration. The system is consisted of a tank (length, L, height, H, being $L >> H$, and width of unity), a taphole of finite diameter, d, located at a height H_d from the bottom, and two layers of immiscible liquids (*m*: molten metal, *s*: molten slag) with densities ρ_m and ρ_s, and viscosities μ_m and μ_s, and a layer of gas (*a*: air) at the top with density and viscosity equal to ρ_a and μ_a. The interface between the liquid layers is initially located at a height, h_m from the taphole centre-line and the thickness of the upper liquid layer is h_s. By opening up the taphole, the liquid *m* flows out at a discharge rate, Q.

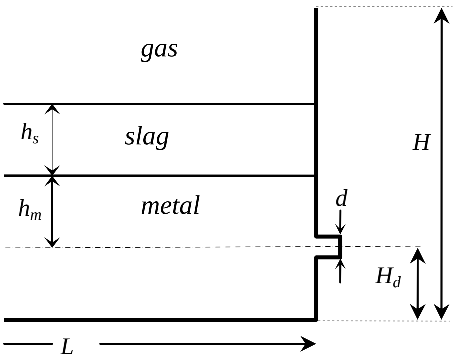


Figure 1: Schematic diagram of geometry.

Based on dimensional analysis, the main parameter controlling the flow of the liquid-liquid or liquid-gas interface is the Froude number defined in terms of line discharge rate, Q, the vertical separation of the line sink and interface at far hand, h,[1] and the reduced gravity, that is, $g' = (\Delta\rho / \rho_s)g$, where $\Delta\rho = \rho_m - \rho_s$. Craya (1949) defined the Froude number for line sinks (slots) as

$$Fr = \frac{Q}{\sqrt{g'}h^{3/2}}, \quad (1)$$

[1] According to the diagram of Fig.2, this distance is h_m for the metal/slag interface and, $h_m + h_s$, for the slag/gas interface.

and for point sinks (orifice) as,

$$Fr = \frac{Q}{\sqrt{g'}h^{5/2}}, \quad (2)$$

assuming that the sink has negligible diameters compared to h. In equations (1) and (2), both Q and h vary with tapping time. When d is comparable with h, the Froude number can be defined based on d as the relevant diameter:

$$Fr_d = \frac{Q}{\sqrt{g'}d^{3/2}}, \quad (3)$$

for line sinks, and,

$$Fr_d = \frac{4Q}{\pi\sqrt{g'}d^{5/2}}, \quad (4)$$

for point sinks.

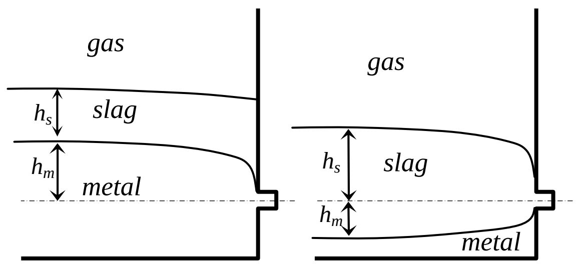
As the Froude number reaches a critical value, the interface stagnation point on the reservoir wall suddenly drops towards the sink (Fig. 2*a*). Assuming that the flow is inviscid, Craya (1949) employed the Bernoulli equation on the interface between the liquids and obtained the critical Froude numbers for the sudden drawdown the liquid-liquid interface towards the sink ($Fr_d =$ 1.5 for line sinks and 2.6 for point sinks). The theoretical correlation for the minimum dimensionless clearance from the taphole before entrainment occurs can be, therefore, derived as:

$$\frac{h_{cr}}{d} = 0.76 Fr_d^{2/3}, \quad (5)$$

for line sinks, and,

$$\frac{h_{cr}}{d} = 0.62 Fr_d^{2/5}, \quad (5)$$

for point sinks.



a) b)

Figure 2: Different flow regimes of tapping flow.

As the Foude number rises (due to higher discharge rate or less separation, h) a super-critical situation is reached where the interface uncovers the taphole and entrainment of the upper liquid into the sink occurs (simultaneous tapping, Fig. 2*b*). As the drainage process continues, the liquid-liquid interface will eventually reach the taphole level and pass it. During this period, the surface of the upper liquid may also tilt towards the sink, and the liquid-liquid interface which is now located below the sink level is drawn up towards the sink (Fig. 2*b*).

The application of Craya's model for viscous liquids has been tested throughout the recent experimental investigation of Liow, et al. (2003) and the results showed that even for the liquids with low viscosities, the agreement with Craya's predictions is only valid for $Fr_d > 1$. Moreover, for fluids with appreciable viscosities, it was found that entrainment occurs at a higher liquid-liquid interface height than what was predicted by the theory. The range of drainage rates is also very wide in industrial furnaces which cause major deviations from theoretical predictions (Smoglie et al., 1987)

It is the objective of this paper to use the CFD techniques in order to perform a parameter study of this multi-variable problem and find out the effect of each variable on the behaviour of the drainage.

MODEL EQUATIONS

The physical model which is used here is the one for the unsteady flow of immiscible liquids in porous media. The governing equations for each phase are the *continuity equation*:

$$\nabla \cdot \vec{v}^{k} = 0 , \tag{6}$$

and the *momentum equation*:

$$\frac{\partial}{\partial t}(\rho^{\alpha}\vec{v}^{\alpha}) + \vec{\nabla}\cdot(\rho^{\alpha}\vec{v}^{\alpha}\vec{v}^{\alpha}) = -\varepsilon\vec{\nabla}P^{\alpha} + \rho\varepsilon\vec{g} + \vec{\nabla}\cdot(\mu^{\alpha}\vec{\nabla}\vec{v}^{\alpha}) - \vec{S}^{\alpha} \tag{7}$$

in which is the porous media viscous resistance to the flow

$$\vec{S}^{k} = \frac{\mu}{\kappa}\vec{v}^{k} , \tag{8}$$

where κ is the permeability (m²) of the packed bed given by the Karman-Kozeny theory:

$$\kappa = \frac{d_p^2}{C_\beta} , \tag{9}$$

where d_p is the particle diameter and, C_β is a dimensionless function of porosity

$$C_\beta = \frac{180(1-\varepsilon)^2}{\varepsilon^3} . \tag{10}$$

NUMERICAL METHODS

The FLUENT software has been used in order to perform the simulations. The Volume of Fluid (VOF) method together with the geometry reconstruction scheme has been chosen in order to accurately calculate the sharp interface between the immiscible liquids. The method is also capable of including interfacial tensions and wall adhesion effects whenever these effects are considerable in the system. The porous media boundary condition available in the software was used in order to model the packed bed effect. The model is based on the formulations given in equations (8) to (10).

SIMULATION SETUP

Flow Geometry

The flow geometry is set as follows. A 2-D rectangular reservoir with length 4 m and height 1.5 m has been considered where the taphole was located on the side at a centre-line height 45 cm from the bottom. The taphole diameter was set to 10 cm, for the large-diameter case, and 5 cm for the small-diameter case. Two configurations of tapping are considered: A) the liquid-liquid interface is located above, and B), below the level of taphole. For configuration A, the reservoir was filled with the heavy liquid up to a height of 45 cm over the taphole centre-line, and the light liquid was filled up to a height of 45 cm over the heavy liquid surface (Fig. 2 *a*). For configuration B, the reservoir was filled with the heavy liquid up to a height of 15 cm below the taphole centre-line, and the light liquid was filled up to a height of 45 cm over the level of taphole centreline. (Fig. 2 *b*). Such configurations are similar to practical situations in the blast and smelting furnaces. The corresponding discharge rates at these configurations are high enough to ensure that all the flow regimes discussed in the previous section to occur.

Material Properties

In the first part of the simulations, the effect of density difference between the layers is studied. The density of the heavier liquid is set to 7000 kg/m³ which is a value close to that of most of the molten metals (Slag Atlas, 1995). The density of the lighter liquid is defined by a density ratio, $\alpha = \rho_s / \rho_m$, equal to 0.2, 0.5, 0.65, and 0.8. The resulting densities and associated reduced gravities are given in Table 1. In the simulations related to the density-difference effect, the viscosity in both layers is kept identical and equal to the low value of 0.001 kg/m.s. Simulations are performed for each of the two configurations, A and B.

ρ_m=7000 kg/m³				
α	0.2	0.5	0.65	0.8
ρ_s	1400	3500	4550	5600
g'	39.2	9.8	5.27	2.45
CFD Run	DR0.2	DR0.5	DR0.65	DR0.8

Table 1: Density variations.

Simulations are carried out in the second part in order to study the effect of viscosity difference between the layers. The density ratio between the two layers is fixed to 0.65, and, the viscosity of the heavier layer is set to 0.005 kg/m.s. The viscosity of the lighter liquid is then varied according to the values given in Table 2.

μ_m=0.005 kg/m.s				
β	1	20	200	2000
μ_s	0.005	0.1	1	10
CFD Run	VR1	VR20	VR200	VR2000

Table 2: Viscosity variations.

The obtained viscosities are in accordance with the range of typical metallurgical slags (Slag Atlas, 1995). Simulations are performed for both configurations, A, and, B.

In the third part of the simulations, the effect of the presence of a packed bed of particles on the tapping behaviour is studied. It is assumed that the packed bed is uniform in porosity and permeability everywhere in the flow domain. The magnitude of porosity and permeability are varied according to the values given in Table 3. The density ratio as well as the viscosity ratio between the two layers is fixed to 0.65, and, 20, respectively. Simulations are performed only for configuration A due to the reasons which will be discussed later.

ε	d_p(mm)	κ(m^{-2}) ($\times$ 10^{-07})	CFD Run
0.35	25	3.52	P35d25
0.45	10	1.67	P45d10
	25	10.5	P45d25
	40	26.8	P45d40
0.55	25	28.5	P55d25

Table 3: Porosity and permeability variations.

RESULTS AND DISCUSSIONS

In total, 25 simulation cases have been performed and the behaviour of tapping in each case has been carefully studied. In experiments, measuring the exact location of the interface between the liquid layers is not accurate and the onset of entrainment is a "matter of judgement" (Wood, 2001). This problem is solved by the aid from the numerical simulations in which the location of the interface stagnation point on the left wall can be detected accurately.

For the case of tapping from a packed bed, the numerical simulations are validated by the experiments performed by Tanzil et al (1984). The positions of the interfaces at different times during the tapping period showed acceptable agreements with similar results obtained from the experiments.

Before proceeding to the analysis of the effects of variation in different flow parameters on the tapping behaviour we should mention here that the surface tension and interfacial tension effects are negligible in flow geometries where the taphole diameter is large compared to the capillary length, and the flow rates are high. Nonetheless, a simulations were performed using the surface tension of the metal equal to 1.2 N/m, surface tension of the slag equal to 0.5 N/m, and metal-slag interfacial tension equal to 0.6 N/m and no effects were found in the results. An additional simulation was performed were the interfacial tension between the metal and slag was doubled and identical results were obtained.

Buoyancy Effects

Figure 3 shows the discharge rates of the liquid layers corresponding to the configuration A at different density ratios. The onset of the supercritical entrainment of the lighter layer is delayed as the density difference between the two layers increases. For all cases, the Fr number is minimum during the initiation of the flow and it gradually increases with the drop of the interface height. From the animations made out of the simulations (numbers 1, 2, 3, 4 in the list of animation in the Appendix) it was observed that the interface is immediately drawn down during the initiation of the flow for the case α=0.8, whereas for other cases, the drawdown did not occur until that the interface reaches a critical height. For the case α=0.65, it was observed that there exists a steady-state motion of the liquid-liquid interface until its motion passes to an unsteady regime. This unsteady regime ends with a cusp form of the interface just before it passes to the critical and supercritical regime. All these observations are in accordance to the theoretical predictions (Tyvand, 1994, Hocking, 1995, Hocking & Forbes, 2001). The wavy curves in Figure 3 show the existence of lateral waves inside the reservoir during the tapping period.

Viscosity Effects

Figure 4 shows the discharge rates of the liquid layers at α=0.65 with variation of the viscosity of the lighter layer. The curves correspond to the configuration B where the lighter layer is flowing out and the heavier layer is entrained into the taphole from levels below the level of the taphole. With decrease in discharge rate due to the loss of hydrostatic head, the flow rate of the entrained heavier layer decreases, and finally, the entrainment yields. It is clearly seen from the figures that the viscosity variation of the lighter layer does not affect the tapping behaviour. Not only the tapping rates, but also, the onset and yield of the entrainments are all identical.

Note that in the set of simulations shown in Figure 4, only the effect of viscosity is explored without considering the presence of a porous medium. As expected the fluid viscosity has a small impact on tapping if the furnace is open without formation of a packed bed of solid material.

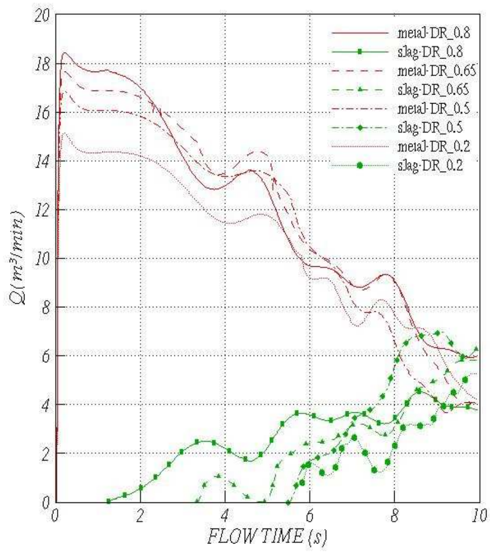


Figure 3: Tapping rates of the two liquid layers at different density ratios (configuration A).

Packed-bed Effects

In order to study the effect of presence of packed bed on the tapping behaviour, the density and viscosity ratios are kept fixed and equal to 0.65 and 20, respectively. In Configuration A, this corresponds to tapping the heavy liquid while the lighter liquid with much higher viscosity lies on the top. Figure 5 shows the effect of the presence of packed bed on the tapping rates. The tapping rate of the heavier liquid is considerably lower. It is observed that the onset of entrainment of the lighter liquid is considerably advanced in time. Moreover, the tapping rate of the entrained liquid starts to decrease shortly after the onset of entrainment, whereas, in the other case where the packed bed is not present, the entrainment occurs later in time but the tapping rate of the entrained liquid keeps increasing. Figure 6 shows the profile of the interfaces after 7 seconds. It can be seen that the gas is also entrained into the taphole, a considerable amount of the lighter liquid is remained inside the reservoir, and the heavier liquid is entrained into the taphole from the levels considerably below the level of the taphole.

Figures 7 and 8 shows the effects of variation of porosity and permeability on the tapping rates, respectively. Reducing the permeability of the packed bed effectively reduces the tapping rate of the heavier liquid but has minor effects on the tapping rates of the lighter but more viscous liquid.

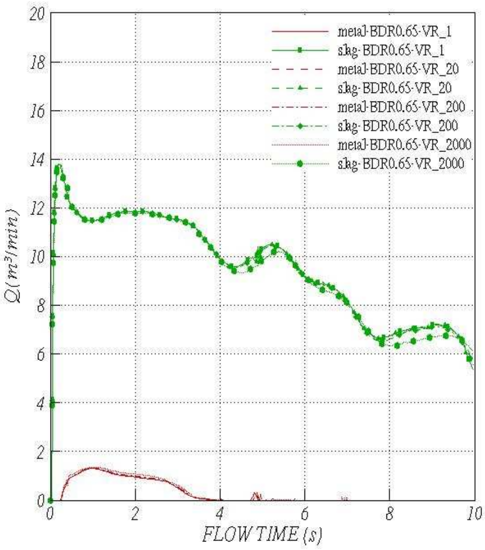


Figure 4: Tapping rates of the two liquid layers at different viscosity ratios (configuration B).

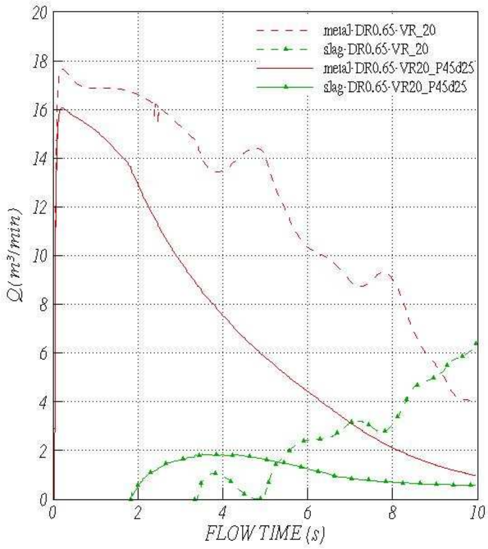


Figure 5: Packed-bed effect (configuration A).

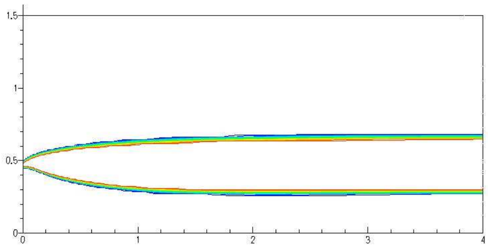


Figure 6: Profile of liquid-liquid and liquid-gas interface in the presence of packed bed.

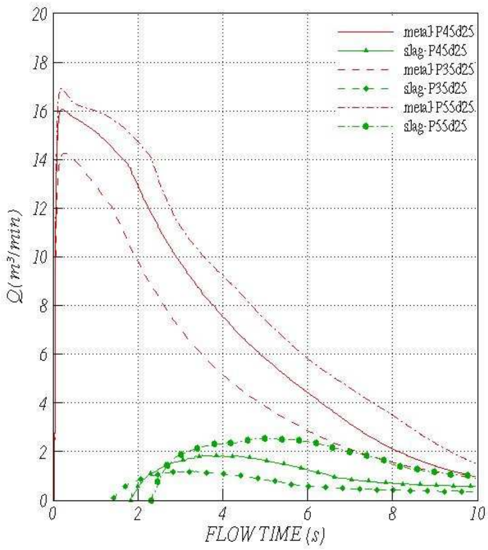


Figure 7: Porosity variation (configuration B).

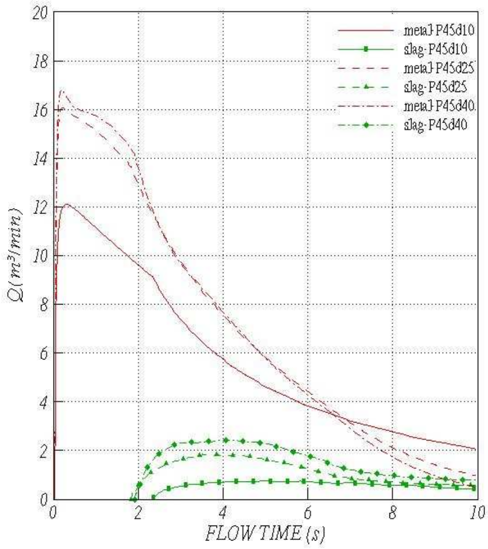


Figure 8: Permeability variation (effect of particle size in the coke-bed) (configuration A).

CONCLUSION

The physical mechanisms and the importance of several flow parameters in determining the tapping behaviour and the motion of the liquid-liquid interface during the tapping period is clarified by the aid from CFD techniques and performing a parameter study on the tapping problem.

From the results obtained in this study of the influence of density- and viscosity-difference on tapping behaviour, it can be concluded that in the absence of a packed bed, the viscosity difference between the metal and slag layers has negligible influence on the shape and motion of the slag-metal interface. It was found that only the density ratio between the two liquid layers can modify buoyancy forces and inertial forces in such a way that different regimes of interface motion inside the taphole can be created. A Froude number is the only dimensionless number which characterizes the motion of the interface between the two layers, even if any of the liquids has large viscosities. It is therefore expected that a correctly formulated Froude number should be able to reflect the critical conditions in the case where a packed bed of solid materials inside the slag-metal layer is non-present.

However, in the presence of a packed bed the behaviour of the tapping is quite different. The presence of porous material result in reduced metal and slag flow, but somewhat unexpectedly porous blockage has the effect that slag may be tapped earlier than for a reference situation without the presence of a packed bed. Even so, the presence of a packed bed gives a reduced slag tapping yield for the investigated time span.

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APPENDIX

List of animation files:

1. DR0.8.mpeg
2. DR0.65.mpeg
3. DR0.5.mpeg
4. DR0.2.mpeg
5. P45d25.mpeg