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Review

Interphase mass transfer between fluids in subsurface formations: A review

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ABSTRACT

This paper presents a review of the state-of-the-art on interphase mass transfer between immiscible fluids in porous media with focus on the factors that have significant influence on this process. In total close to 300 papers were reviewed focusing to a large extent on the literature relating to NAPL contamination of the subsurface. The large body of work available on this topic was organized according to the length scale of the conducted studies, namely the pore, meso and field scales. The interrelation of interphase mass transfer at these different scales is highlighted. To gain further insight into interphase mass transfer, published studies were discussed and evaluated in terms of the governing flow configurations defined in terms of the wettability and mobility of the different phases. Such organization of the existing literature enables the identification of the interfacial domains that would have significant impact on interphase mass transfer. Available modeling approaches at the various length scales are discussed with regard to current knowledge on the physics of this process. Future research directions are also suggested.

Contents

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Nomenclature

Roman letters

A	absolute interfacial area (L^2)
A_{ia}	the air–water interfacial area normalized by porous medium volume (1/L)
A_{ij}	cross section area of the pore throat between pore i and j (L^2)
A^*_{NW}	interfacial area between wetting and non-wetting phase per unit pore volume (1/L)
$A_{na,i}$	interfacial area in pore i (L^2)
A^*_{sN}	interfacial area between solid and non-wetting phase per unit pore volume ($A^*_{sN}=0$ if $S_w=1$) (1/L)
A_w	cross sectional area in water filled pore throat (L^2)
a	specific interfacial area (1/L)
α^{wn}	effective specific interfacial area (meniscus interfacial area per unit volume of porous media (1/L)
C	solute concentration (M/L^3)
C_a	solute concentration at the center of each subdivision (M/L^3)
$C_{a,i}$	solute concentration in pore i (M/L^3)
C^S_a	solute equilibrium concentration (M/L^3)
C_b	concentration in bulk phase (M/L^3)
C_{eq}	solute equilibrium concentration (M/L^3)
C_i	solute concentration in pore i (M/L^3)
C^{in}_i	solute concentration entering pore i (M/L^3)
C^{out}_i	solute concentration leaving pore i (M/L^3)
C^{in}_j	solute concentration entering pore j (M/L^3)
C_{NW}	constant of integration
C_{out}	effluent concentration (M/L^3)
C_s	solute equilibrium concentration (M/L^3)
$C_{(s)}$	solute equilibrium concentration (M/L^3)
C^{in}_t	solute concentration entering pore throat (M/L^3)
D	molecular diffusion coefficient (L^2/T)
D_m	molecular diffusion coefficient (L^2/T)
D_y	dispersion coefficient in y direction (L^2/T)
d_s	diameter of spherical blobs (L)
d_m	grain diameter (L)
E	interphase mass transfer rate divided by the interfacial area
E_d	energy dissipation factor (Eq. (10))
E_d	normalized average effluent conc. (Eq. (25))
E_{wn}	interfacial area production rate (1/L T)
e_i	separation distance between nodes (L)
e_{wn}	strength of change in specific interfacial area (1/L)
$F^{(j)}$	force acting on position x of component j ($M L/T^2$)
F_{ij}	mass flux between pore i and j ($M/L^2 T$)
$F(x_j-x_i, y_j-y_i, z_j-z_i)$	erfc type transport function (open format can be found in [220])
G_{ij}	pore conductance between pores i and j ($T L^4/M$)
G_{jk}	interaction strength parameter between component j and k (Eq. (29))
GTP	ganglia to pool ratio
I_i	interphase mass transfer term
K_f	ratio of NAPL density to the contaminant conc. in the flushing solution in stream tube i (Eq. (19))
K_l	mass transfer rate coefficient (i.e., mass transfer coefficient lumped with interfacial area) (1/T)
$\bar{K}_s$	average hydraulic conductivity of domain (L/T)
$k_{f1,2}$	mass transfer coefficient (L/T)
l	length of hypothetical film thickness (L)
l	length of the pore throat (Eq. (23)) (L)
l_t	length of the pore throat (L)
L	length in x direction (L)
M	solute mass transferred between phases (M)
$M_{(t)}$	NAPL mass at time t (M)
M_i	number of interfaces connected to pore i
M_0	initial NAPL mass (M)
m	parameter determined with respect to uniformity coefficient of the medium (Eq. (7))
N	number of subdivisions (Eqs. (13) and (14))
N	number of adjacent pores to pore i (Eq. (22))
N_i	number of pores connected to pore i
N_i	molar flux of component i (Eq. (30)) ($mol/L^2 T$)
n	parameter determined with respect to uniformity coefficient of the medium (Eq. (7))
P_{ij}	pressure difference between pore i and j ($M/L T^2$)
P^{crit}_c	critical disjoining pressure ($M/L T^2$)
Pe	Peclet number
Q_{ij}	flow rate between pores i and j (L^3/T)
Q^w_{ij}	flow rate of water between pore i and j (L^3/T)
Q^α_{ij}	flow rate of phase α between pore i and j (L^3/T)
q	superficial aqueous phase velocity (L/T)
$\bar{q}$	average Darcy velocity (L/T)
Re	Reynolds number
R_i	retardation factor of stream tube i
R_t	pore throat radius (L)
SA	specific surface area of porous medium (L^2/M)
S^α_i	local saturation of phase α in pore i
$\breve{S}_i$	trajectory average NAPL saturation of stream tube i
S_m	monolayer saturation
S_w	wetting phase saturation
s	normalized surface area of the porous media
Sh	Sherwood number
Sh'	modified Sherwood number
t_i	nonreactive travel time in stream tube I (T)
U	velocity (L/T)
U_x	velocity in x direction (L/T)
$V_{a,i}$	volume of pore containing water (L^3)
V_i	volume of pore I (L^3)
V_s	volume of NAPL in shape of spherical blobs per unit volume of medium (Eq. (12)) (L^3/L^3)
V_s	volume of site (pore i) (Eq. (23)) (L^3)