Cold Temperature Nitrification of Lagoon Wastewater using a Biologically Active Filter (BAF)

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Abstract
The paper describes the results of a pilot test of a biologically active filter (BAF) for cold temperature nitrification of lagoon wastewater. Consistent nitrification to fractional levels was achieved due to the heat transfer characteristics of BAF. The performance results are discussed and the convection heat transfer characteristics of the reactor are discussed to explain the effectiveness of the reactor as a heat exchanger.

Keywords
Cold temperature nitrification; BAF; convection heat transfer in a porous medium

INTRODUCTION

Lagoons or stabilization ponds are terms for a group of suspended growth systems that do not have downstream clarification and no solids recycle. Lagoons have been used to stabilize biodegradable organic matter; although nitrification has also been observed in some systems. The first recorded installation of a lagoon, in the United States, was at San Antonio, Texas in 1901, (EPA 1983). Prior to the widespread emergence of nutrient removal over 7000 lagoons were installed in the United States; however, as nitrogen requirements have become more prevalent many of these systems are facing either ammonia or total nitrogen limits. For lagoons located in areas that experience cold temperatures, meeting ammonia or total nitrogen limits during the winter may be problematic.

In the Township of Waverly, Lackawanna County, Pennsylvania, which has been operating two lagoons in series since September 1986, a pilot study was conducted to augment the lagoons with a biologically active filter (BAF) in order to maintain nitrification throughout the summer and winter months. Each facultative lagoon is 91 m x 37 m. by 3 m. with a 3:1 slope. The permitted wet weather flow is 1,893 m^3/d with a normal permitted flow of 1,363 m^3/d. The average flow is approximately 1,136 m^3/d. Currently, the plant has seasonal ammonia limits. From May through October the average monthly effluent ammonia-nitrogen limit is less than 4 mg/l with an instantaneous maximum limit of 8 mg/l. From November through April the average monthly effluent ammonia-nitrogen limit is 12 mg/l with an instantaneous maximum limit of 24 mg/l. Although the plant generally meets the permit requirements many of the winter violations are likely attributable to water temperatures as low as 0°C. In addition, the plant discharges into the Susquehanna River Basin and hence into the Chesapeake Bay, which means that more stringent nutrient requirements, including total nitrogen limits, are scheduled to be imposed. For this reason, the Township chose to investigate a process that may be used in conjunction with the existing lagoons that will achieve low ammonia levels throughout the coldest months.

METHODS

The pilot unit was a deep-bed sand biologically active filter (BAF), consisting of an underdrain, support gravel, and filter media as illustrated in Figure 1. The stainless steel underdrain located at the bottom of the reactor and provides support for the gravel and media, and for even distribution of air and water into the reactor. The underdrain has a manifold and laterals that distribute the air evenly over the entire filter bottom. The design allows for both air and water to be delivered simultaneously or separately, via individual pathways, to the bottom of the reactor. On top of the underdrain was 0.46 m of gravel, in four different sizes laid down in five layers. The gravel was placed in order of descending size, (i.e. the largest at the bottom layer). Its' purpose was to keep the smaller sand media from penetrating down into the plenum below the underdrain. Above the gravel was 1.22 m of coarse round, silica sand media. The sand media has a 3.2 mm nominal diameter producing a media porosity of approximately 35%. The media specific surface area was 850 m^2/m^3.

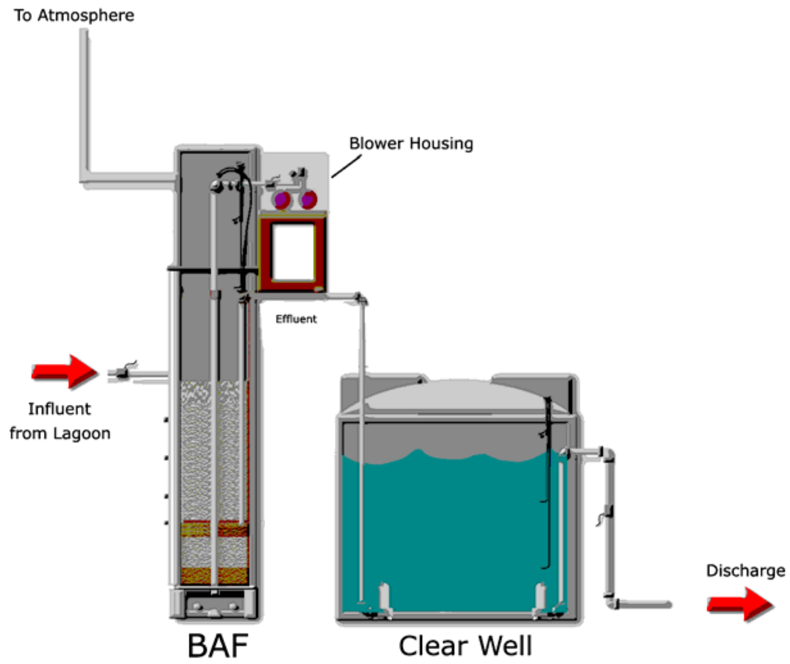

Figure 1. Pilot Plant Operated at the Waverly Township Facility

The reactor was 0.762 m in diameter, with 1.22 m of media, with an overall height of 3.81 m. The process air was supplied to the reactor intermittently by a 93-watt rotary vane air compressor, at a rate of 0.012 m^3/min. Four sampling ports were located at various depths within the media from which samples were collected and the temperature recorded. Due to this method the temperatures represent a bulk cross sectional average.

There was periodic internal recycle from the clear well back to the filter. Sludge was wasted from the filter by a backwash of both air and water and return to the lagoon. The backwash air was supplied by the process air compressor and by a 1.1 KW rotary lobe backwash air compressor. The design volumetric flow for the backwash air was 0.708 m^3/min. Backwash water was provided by one pump, located in the clear well and connected to the filter effluent line. The backwash water flow rate was 0.095 m^3/min.

The pilot test was conducted from September 2011 to April 2012 with the objective of demonstrating the ability of the system to receive relatively cold wastewater while maintain nitrification to fractional levels of ammonia.

RESULTS

The maximum influent ammonia concentration was 12.1 mg/l with a median value of 8.41 mg/l. The average effluent concentration was 0.59 mg/l and the median was 0.10 mg/l. The average flow rate to the reactor was 6.383 m^3/d, above the design flow of 3.785 m^3/d. The average nitrification rate throughout the test was 93.6% with a median of 97.6%. For a loading of 0.132 kg-NH_3-N/m^3-day and temperature of 3.3°C an effluent ammonia concentration of 0.1 mg/l was achieved, as shown in Figure 2. Figure 2 also indicates that during the test the effluent ammonia concentration exceeded 1.0 mg/l on six occasions; however, only two of these were at a temperature below 5°C. The plot of ammonia removal rate versus temperature, (Figure 3) indicates that as the temperature went up the removal rate went down. This is due to increased nitrification in the lagoon at these temperatures. As expected the higher influent ammonia concentration to the BAF occurred during the coldest period of the test.

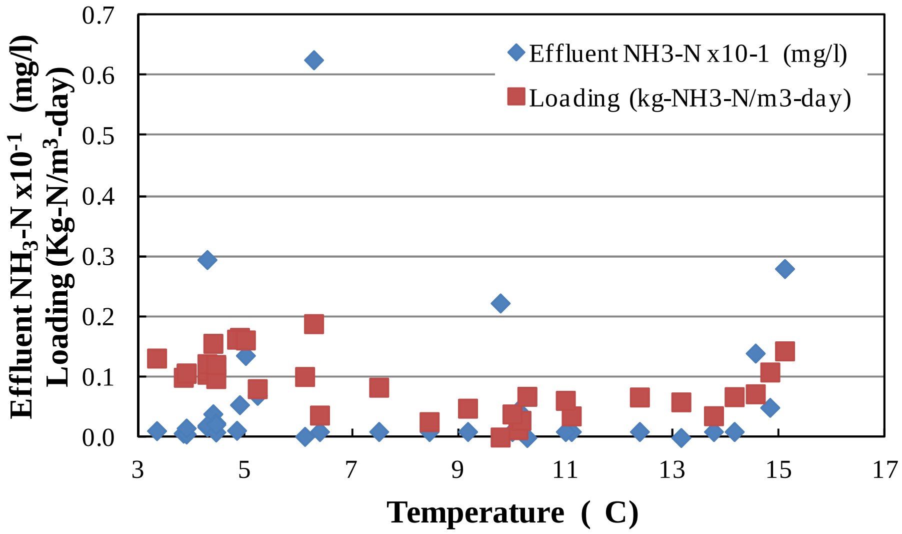

Figure 2. Ammonia Loading and Effluent Concentration versus Temperature

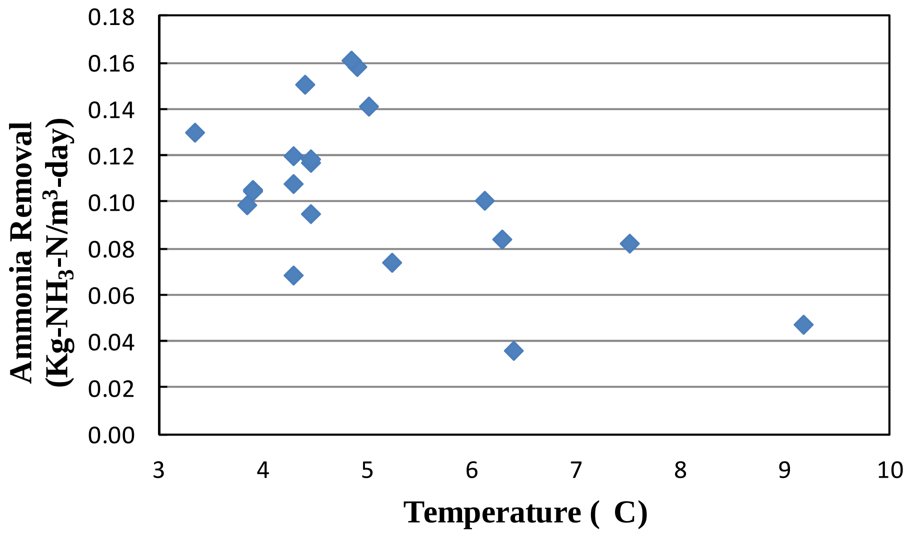

Figure 3. Ammonia Removal versus Temperature

The influent wastewater temperature ranged from 3.3ºC to 15.1ºC on days that samples for the laboratory were collected. However, the minimum recorded influent temperature from the lagoon was 1.9 and the corresponding wastewater temperature within the filter was 4.5 ºC. In Figure 4 the temperature of both the influent wastewater and wastewater within the filter are plotted against the flow rate. The graph indicates in all cases the wastewater temperature increased within the filter.

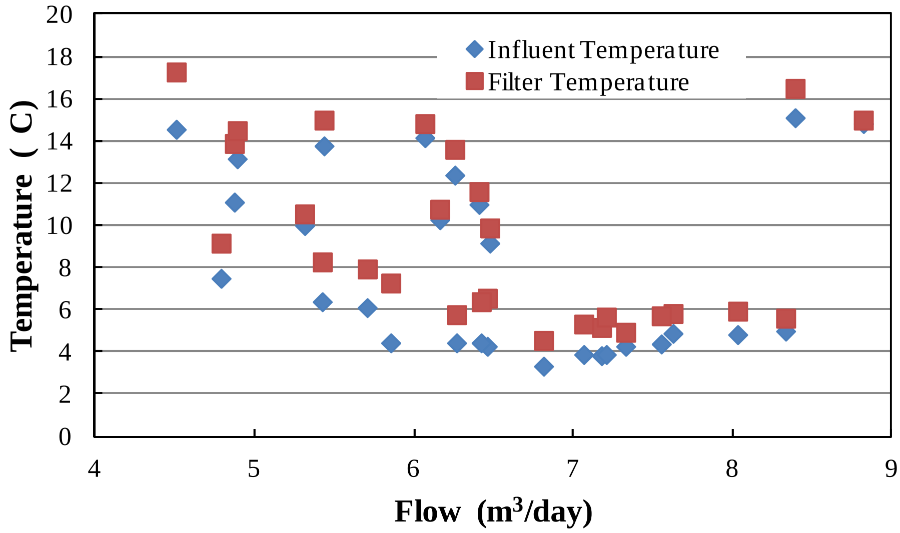

Figure 4. Influent and Filter Wastewater Temperature versus Flow

DISCUSSION

All submerged attached growth bioreactors (SAGBs) or BAFs, utilized in the water and wastewater industry, are essentially tubes packed with a porous media that are designed to treat wastewater. However, examination of the transport properties through porous media indicates that with the selection of certain material as the media the reactors may also function as a heat exchanger augmenting the desired treatment.

Experimental Analysis:

Application of the first law of thermodynamics to a control volume around the reactor shown in Figure 5, gives the following:

$$\frac{d(E_{CV})}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e\right)$$

neglecting: kinetic and potential energy, that the work is zero and noting that

$\dot{m} = \dot{m}_i = \dot{m}_e$ yields:

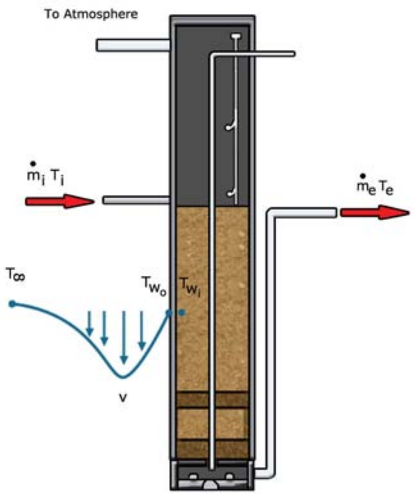

Figure 5. Reactor Control Volume

$$\frac{d(E_{CV})}{dt} = \dot{Q}_{CV} + \dot{m}(h_i - h_e)$$

$$\dot{Q}_{CV} = \frac{d(E_{CV})}{dt} - \dot{m} c_p \Delta T$$

Once the energy generated in the reactor, by the biochemical reactions, is calculated, and using the temperature increase measured during the pilot test, this equation can be used to determine the energy required to raise the temperature of the wastewater.

To determine the heat generated from the biological activity, it was assumed that the only reaction occurring in the reactor was nitrification. Therefore, the energy is obtained from the oxidation-reduction reaction:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

$$G_f^{\circ'} = G_{f\,(products)}^{\circ'} - G_{f\,(reactants)}^{\circ'}$$

$$G_f^{\circ'} = -349.01 \frac{KJ}{mole}$$ (Madigan et al. 2012)

The results of applying both equations are plotted in Figure 6 and indicate that the heat generated from the nitrification of the relative low concentration of ammonia in the lagoon effluent are an order of magnitude lower than the energy required to raise the temperature of the water to level recorded. These values appear to be on the same order of magnitude as the heat generated from nitrification reported by Daverio et al. (2003).

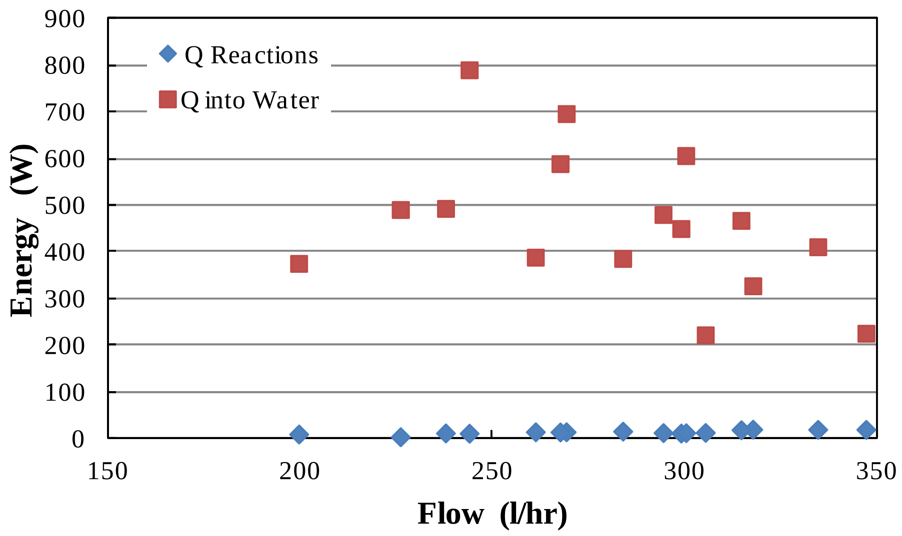

Figure 6. Energy from Reactions and Energy Required to Heat the Water versus Flow

Theoretical Analysis:
Returning to the control volume in Figure 5 the energy balance around the system must include natural convection around the reactor and clear and forced convection through the porous medium (i.e. media & fluid) within the reactor.

For natural convection:

$$Q = h\mathrm{A}(\mathrm{T}_{\mathrm{w\,o}} - \mathrm{T}_{\infty})$$

$$h = 1.42\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \qquad \text{(Holman, 1981)}$$

In order to consider the natural convection conduction through reactor wall needs to be considered and is determined from assuming steady state, one dimensional conduction and given by:

$$Q = -k\mathrm{A}\frac{\mathrm{dT}}{\mathrm{dx}}$$

Setting Q equal to one another and solving by iteration we get T_{wi} and T_{wo}

$$-k\mathrm{A}\frac{\mathrm{dT}}{\mathrm{dx}} = 1.42\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}}\mathrm{A}(\mathrm{T}_{\mathrm{w\,o}} - \mathrm{T}_{\infty})$$

Having obtained T_{wo} the heat transfer coefficient for natural convection (h) may be determined and therefore $Q_{\text{(natural convection)}}$ can also be obtained.

The next step is to determine the heat transfer within the filter. Again, application of the first law of thermodynamics to the porous media zone results in

$$\left[\phi\rho_f c_{p_f} + (1-\phi)\rho_s c_s\right]\frac{\partial T}{\partial t} + \rho_f c_{p_f} u\frac{\partial T}{\partial x} = \left[\phi k_f + (1-\phi)k_s\right]\frac{\partial^2 T}{\partial x^2} + (1-\phi)q_s''' + u\left(-\frac{\partial P}{\partial x} + \rho_f g_x\right)$$

Before proceeding to an empirical solution; several points may be deduced from this equation. Assuming a one dimensional model with parallel conduction, the thermal conductivity of the porous medium becomes a combination of the thermal conductivity of the fluid and of the media:

$$k_m = \phi k_f + (1-\phi)k_s \qquad \text{(Bejan, 2004)}$$

The thermal inertia of the medium is a function of the individual inertia of both the fluid and the media (i.e. solid) and is expressed as:

$$\sigma = \frac{\phi\rho_f c_{p_f} + (1-\phi)\rho_s c_s}{\phi\rho_f c_{p_f}} \qquad \text{(Bejan, 2004)}$$

As the porosity of the medium increases, the rate of internal heat generation per volume of the porous medium decreases.

$$q''' = (1-\phi)q_s''' \qquad \text{(Bejan, 2004)}$$

The solution for the energy equation for a tube with a porous media with fully developed heat transfer is expressed as a constant Nusselt number (Rohsenow and Choi, 1961, Nield and Bejan, 1999 and Bejan, 2004).
Assuming a constant heat flux:

$$Nu_D = \frac{q''}{T_{w(x)} - T_{m(x)}}\left(\frac{D}{k_m}\right) = 8$$

Solving the above equation for q'' and multiplying it by the surface area of the porous media section of the filter will give the energy input to the fluid with the filter. In Figure 7 the heat transfer measured from the temperature raise of the water is plotted against the calculated temperature of the water. The agreement of the measure versus calculated values are in agreement given the experimental accuracy and the assumptions made. For example, in order to simplify the analysis the process air supplied to the reactor was not accounted for. Although it has been stated that heat energy in the liquid may be removed by the aeration process in an activated sludge reactor, (Jördening and Winter, 2005), the effect of aeration on this reactor is not clear and was neglected in the analysis. The reason for this is that the reactor was intermittently aerated for approximately 45 to 60 minutes per day. Additionally, the Reynolds number for the forward (downward) flow of was approximately 8 indicating the equations for porous media are valid. However, the Reynolds number of 170 for the return flow is indicative of turbulence within the porous medium. The equations used are applicable in the laminar region only.

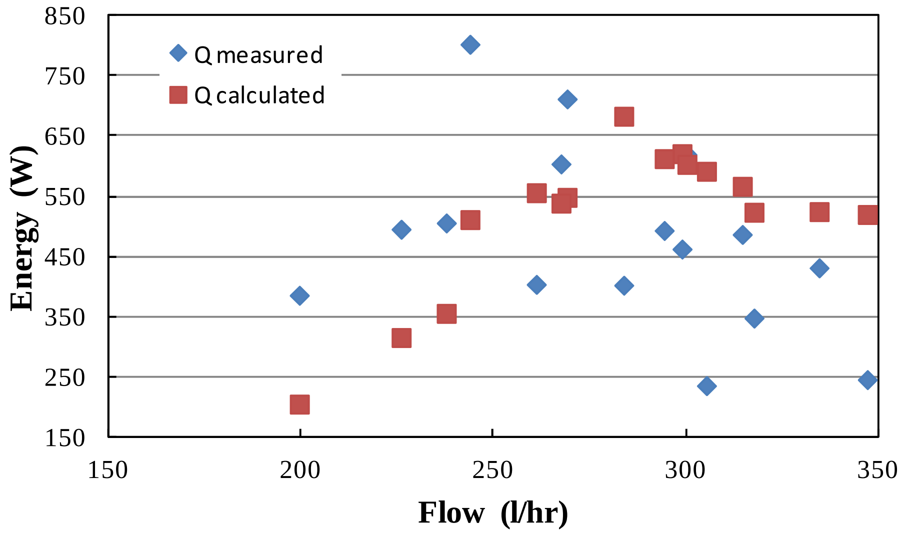

Figure 7. Energy Input to Wastewater, Measured and Calculated versus the Flow

Despite these assumptions the calculated values are within the range of the measured values to support the premise that the temperature increase of the wastewater was due to the physical design of the reactor (i.e. the porous medium). These results are explained by the heat transfer augmentation (Nield and Bejan, 2006). Comparing the Nusselt number for full developed flow in a pipe without porous media is similar to the expression given above, except that the combine conductivity k_m is replaced by k_f of the fluid. The augmentation is approximately ratio of the convection heat transfer coefficients:

$$\frac{h_{x(porousmedia)}}{h_{x(nonporousmedia)}} \approx \frac{k_m}{k_f} \qquad \text{(Nield and Bejan, 2006)}$$

which for this reactor is equal to 3.675. Considering the augmentation effect and the effect of porosity on the internal heat generation, assuming the biofilm around the media causes it to act as heat source, then proper choice of both media and porosity could result in a more effective reactor for cold weather applications.

CONCLUSIONS

The results of the pilot indicate that consistent nitrification was achieved at low temperatures. Although the data reported here was only that which was sampled at an outside lab and the lowest temperature for this data was 3.3 °C. Additional, data sampled with Hach kits indicated fractional ammonia levels with an influent water temperature of 1.9 °C and a corresponding temperature

within the filter of 4.5 °C.
The loading rates achieved in this test were modest and any additional test should include an ammonia feed system to increase the loading in the event that effluent from the lagoon has a lower than desired ammonia concentration.
The physical design of this BAF provided a heat transfer augmentation of approximately 3.6 due to the choice of silica sand (i.e. quartz) as the media. The result was a stable temperature, within the porous medium, throughout the winter.
The pilot plant was constructed within a building that was maintained at approximately 10°C, the full scale system will be below grade. In addition the section of the reactor with the media will be below the frost line will be surrounded by earth. Therefore, the mode of heat transfer will be by conduction and not natural/free convection, which will likely be more effective with respect to energy transfer.
The full scale design for the Waverly, Pennsylvania treatment plant is estimated to cost 1.5 million dollars as opposed to 5 to 6 million dollars for a completely new treatment plant (i.e. scraping the lagoons). The pilot test demonstrated that this particular biofilm reactor, in conjunction with the existing lagoons, would reduce the overall cost of the upgrade and achieve the current effluent limits as well as the more stringent effluent limits scheduled to be imposed.

NOMENCLATURE

$\frac{d(E_{CV})}{dt}$	Change of energy within the control volume (cv)
$\dot{Q}_{CV}$	Rate of heat transfer across the control volume (cv)
$\dot{W}_{CV}$	Rate of work done on or by the control volume (cv)
$\dot{m}_i$	mass flow rate into control volume (cv)
$\dot{m}_e$	mass flow rate out of control volume (cv)
h_i	enthalpy into control volume (cv)
h_e	enthalpy out of control volume (cv)

$$\frac{d(E_{CV})}{dt} = \dot{Q}_{CV} + \dot{m}(h_i - h_e)$$

$\frac{V_i^2}{2}$	kinetic energy into control volume (cv)
$\frac{V_e^2}{2}$	kinetic energy out of control volume (cv)
gz_i	potential energy into control volume (cv)
gz_e	potential energy out of control volume (cv)
c_p	constant-pressure specific heat, (*c* for a solid)
$G_f^{\circ'}$	Gibb free energy of formation
$Q_{convection}$	heat transfer by convection
$Q_{conduction}$	heat transfer by conduction
h	convection heat transfer coefficient
A	surface area

D	diameter
T_{wi}	temperature of inner wall
T_{wo}	temperature of outer wall
T_{∞}	free stream temperature
T_m	bulk temperature
$T_{w(x)}$	wall temperature at x along axis of flow
$T_{m(x)}$	bulk temperature at x along axis of flow
k	thermal conductivity
k_m	thermal conductivity of the porous medium (fluid & solid)
k_f	thermal conductivity of the fluid
k_s	thermal conductivity of the solid
ϕ	porosity
ρ_s	density of the solid
ρ_f	density of the liquid
$q_s^{''}$	heat transfer per unit area (flux)
$q^{'''}$	heat transfer per unit volume
u	velocity
$\frac{\partial P}{\partial x}$	pressure gradient
σ	thermal inertia of the porous medium
Nu_D	Nusselt number

REFERENCES

Daverio, E., Aulenta, F., Ligthart, .J., Bassani, C., and Rozzi, A. 2003 Application of Calorimetric Measurements for Biokinetic Characterisation of Nitrifying Population in Activated Sludge. *Wat. Res.* **37**, 2723–2731.

Bejan, Adrian, 2004. *Convection Heat Transfer.* Third Edition, John Wiley & Sons, Inc., New Jersey.

Holman, Jack, P., 1981. *Heat Transfer.* Fifth Edition, McGraw Hill Book Company, New York.

Jördening, H. J. and J. Winter. Michael, 2005. *Environmental Biotechnology, Concepts and Applications.* eds. Wiley-VCH Verlag GmH & Company.

Nield, Donald A. and Adrian Bejan, 2006. *Convection in Porous Media.* Third Edition, Springer.

Madigan, Michael T., John M. Martinko, David A. Stahl and David P. Clark, 2012. *Brock Biology of Microorganisms.* Thirteenth Edition, Benjamin Cummings, Boston.