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CFD ANALYSIS FOR ANAEROBIC DIGESTION INSIDE A BATCH DIGESTER AUGMENTED WITH EXTENDED SURFACES

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ABSTRACT

The household batch reactor using cow manure as the substrate generates methane gas used as fuel. This paper presents two-dimensional (3D) axisymmetric using commercial COMSOL 5.5 Multiphysics software. This is a computational fluid dynamics (CFD) model based on conservation equations with the chemical reaction model of anaerobic digestion (AD) processes to investigate the influence of different horizontal circular extended surfaces augmented to the inside digesters on the performance of the anaerobic digestion. Using four batch digesters, D1 with no extended surfaces and D2, D3, and D4 have augmented with four horizontal circular extended surfaces of width 2,4 and 6 cm, respectively. The numerical results showed that the cow manure's velocity distribution depends on the chemical reaction's heat, which produces natural convection currents. Furthermore, the temperature and species profiles of the anaerobic digestion process depended on the extended surface area. The D4 has a maximum methane molar concentration, augmented with a higher extended surface area than other digesters. Simulation results agreed with the experimental literature results of various anaerobic digestion processes: for all cases, the mean absolute present error (MAPE) was less than 10%, which is acceptable.

Keywords: *Anaerobic digestion, CFD, COMSOL, Extended surface.*

1. INTRODUCTION

The traditional biogas production system is based on the biodegradation of organic matter without using oxygen by anaerobic digestion, which is considered a renewable energy source (Treichel and Fongaro 2019). This process encompasses various microorganisms which excrete enzymes which convert substrate complex compounds into products for easy assimilation. Each step comprises its microorganisms genera, which consume chemical components, digest them with aid of enzymes and produce chemical products used by the subsequent step bacteria (Kolbl, Tavčer, and Stres 2017). The bacteria in the fermenter form a synergetic and competing ecology system in which many factors inhibit or thrive in this community. The bacteria are influenced by factors such as temperature, substrate pH, nutrients, C/N ratio, mixing, oxygen, VFA and reactor geometry. These factors may cause toxicity and death or growth and reproduction of bacteria in the reactor if the values of the factors are not within a specific range. Therefore, these factors must be mandatorily considered, continuously observed, and maintained within optimum ranges (Sawyerr et al. 2019). The bacteria near or on a particular surface release enzymes and produce functional monomers for themselves and other types of bacteria (Christy, Gopinath, and Divya 2014; Wang et al. 2018). For example, the propionate conversion process depends on the microorganisms, as seen in Fig. 1, which illustrates the principle interactions in acetogenesis between substrates, microorganisms and enzymes and the products obtained (Treichel and Fongaro 2019).

Microorganisms or bacteria are found in a complicated community with numerous categories that occupy a great surface area. Their wide distribution, metabolic rate, growth and reproduction

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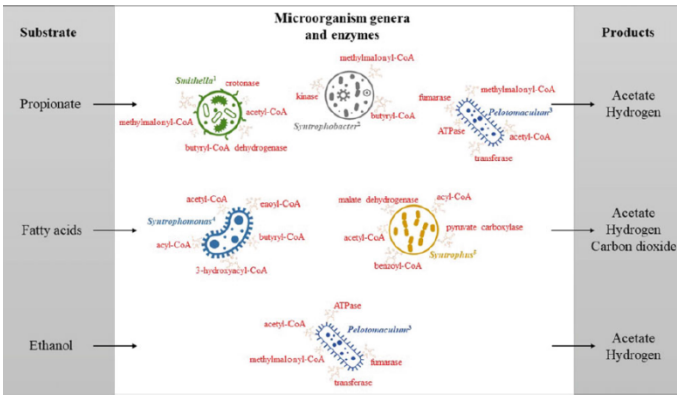


Fig. 1 Overview of the principal interactions in acetogenesis between substrates, microorganisms and enzymes (shown in red) and the principal products obtained (Treichel and Fongaro 2019).

rely on the existence of such surfaces (Deng, Liu, and Wang 2020). Enzymes are protein biopolymers formed in all living cells of microorganisms that excrete high concentrations of extracellular enzymes and are responsible for catalyzing reactions and coordinating various cellular functions. Therefore, as much microorganisms' quantity increases, the enzymes they excrete will increase; hence, chemical reactions will acceralete as a consequence. Acceleration of these chemical reactions results in a more efficient reactor and decreases the production time (Sanchez and Demain 2017).

The AD process involves four steps. In the first step, the complex carbohydrates break down into monosaccharides via hydrolysis. The second step is acidogenesis, where acidogens convert

the monosaccharides into carbon dioxide, hydrogen, and volatile fatty acids (VFAs), such as butyric acid. The third step is acetogenesis, where the VFAs are degraded into acetate. The final step is methanogenesis, where the acetate degrades into methane and carbon dioxide (Deng, Liu, and Wang 2020).

AD is a biochemical reaction completed by cooperation of different microorganisms. Each process of AD is represented and accompanied by chemical reactions. Since these reactions are either endothermic or exothermic, thus it is expected a considerable amount of heat exchange will occur, resulting in temperature differences that produce natural convection currents that redistribute ecosystem microorganisms, generating a new heat generation or absorption map (Zobaa and Bansal 2011).

Recently, the authors investigated the effect of the size and surface area of the digester parameters on the performance of anaerobic digestion, as dealing with Nasir et al. (2015) and Ogunwande and Akinjobi (2017), respectively. Therefore, their results showed that the size and surface area (height-to-diameter ratio of the digester) directly affect the gas production quantity.

Also, the authors investigated factors for high-efficient AD performance. Li, Jha, and Bajracharya (2014), Rathaur et al. (2018), Rajput, Zeshan, and Hassan (2021), Noonari et al. (2020) and Erdiwansyah et al. (2022) focused on the improvisation of biogas production quantity and quality from other co-digestion wastes with their mixtures. Komemoto et al. (2009) examined the effect of temperature on the solubilization and acidogenesis of food waste. Rodríguez, Pérez, and Romero (2013) used the organic portion of municipal solid waste as feedstock under mesophilic (35 ^{o}C) and thermophilic (55°C) conditions to evaluate the specific growth rate of microorganisms. Fedailaine et al. (2015) developed a mathematical model based on biomass mass balances to simulate anaerobic digestion.

Some authors investigated the anaerobic digester's performance by utilising computational fluid dynamics (CFD) to study the mixing behaviour of the fluid flow, energy, and chemical reactions and their effect on anaerobic digestion. Meroney and Colorado (2009) and Terashima et al. (2009) simulated sludge mixing characteristics and properties for full-scale different circular anaerobic digester tanks producing biogas. Leonzio (2018) and Saini et al. (2021) established the best geometrical configuration for a mixing system (mechanical mixing and automated sludge circulation) to save the power used in anaerobic digestion. Wu, Bibeau (2009) analyzed the reaction rate's influence on biogas production for a plug flow anaerobic digester. Wu (2010a) ; Wu (2010b) evaluated twelve turbulence models of a 3D single-phase and multiphase non-Newtonian fluid flow in anaerobic digesters for horizontal pipe by comparing the frictional pressure obtained from CFD with those from a correlation analysis for effective mixing improvement.

Bridgeman (2012), Shen et al. (2013), Mohammadrezaei, Zareei, and Khazaei (2018), and Chen et al. (2019) determined suitable loading sludge, a suitable mixing speed, appropriate blade type, the appropriate number of impellers and evaluated the optimal mechanical mixing method for biogas generation enhancement of anaerobic digester. Martínez et al. (2011),Conti, Saidi, and Goldbrunner (2019) and Dabiri et al. (2021) identified dead zones, established the best geometrical configuration, evaluated the mixer energy consumption and velocity gradient to ensure the highest sludge mixing efficiency inside the full-scale anaerobic digester. Kamarád et al. (2013), Dapelo and Bridgeman (2018) and Mao et al. (2019) investigated the minimum retention time of the fed substrate with different mixing systems for real large-scale anaerobic digesters. Patrícia et al. (2020) and El Ibrahimi et al. (2021) studied and analysed the influence of heating and liquid recirculation on digesters with submerged wastes under mesophilic conditions on the thermodynamic performance of the digester. Acetogenesis and methanogenesis reactions were studied by Azargoshasb et al. (2015) using 3D CFD and population balance equations. They used the Eulerian multiphase and (k – ε) turbulence models to simulate the reaction in hydrodynamics in a reactor with various influent VFA concentrations and hydraulic retention durations (HRT).

Rezavand et al. (2019) developed a 2D entirely Lagrangian computational model to combine mixing and biological response in anaerobic digestion. The diffusion equation provides the mass transfer interactions between the particles to link mixing to biochemical reactions. Using a multiphase CFD model, Jegede et al. (2020) evaluated an optimized Chines dome digester, and the findings were compared to the results of pilot-scale trials. The self-agitation cycles are characterized by steady and improved hydraulic properties and mixing in the designed digester. Zarei et al. (2021) described the hydrodynamic regime of flow and mass transfer of species within the lab scale continuous packed bed with a multi-sized distrusted particles bioreactor, and the anaerobic methanogenesis reactions occur at the particle surfaces.

From the literature above, and to our knowledge, the influence of different horizontal circular extended surfaces around the inside of the batch household digester on the biogas-producing efficient performance has not been previously researched. However, there is little effort to increase surface area without using extended surfaces, such as the work of Nasir et al. (2015) and Ogunwande and Akinjobi (2017). The objective of this paper is to fill this gap by building a 3D axisymmetric model for a batch digester based on the fundamental equations of conservation (mass, momentum, energy, and transport of diluted species) and the fundamentals of the four stages of the biochemical processes of AD (hydrolysis, acetogenesis, acetogenesis and Methanogenesis) using cow dung as the substrate to analyse and determine the effects of the reaction rate, the heat source, and the natural convection from the extended surfaces for improving the quantity and quality of biogas production.

2. CFD MODEL

2.1 Geometry and Principle of Operating

The simulations and modelling were performed on four batch digesters (D1, D2, D3, and D4) fabricated from PVC materials with a volume of 13 L (24 cm in diameter and 30 cm in height). The active working of each digester was at a 22 cm height (75 % working volume) filled with wet cow manure and water at a mixing ratio of 1 kg: 1 L, respectively. The released biogas accumulated in the residual part above the slurry. The horizontal circular PVC extended surface areas were equipped with the four batch digesters, with D1 having no extended surfaces. D2, D3, and D4 were provided with extended surfaces with widths of 2, 4, and 6 cm, respectively. Four layers were distributed prime from below, one of each 5 cm in height for the digester. The geometries of these 3D axisymmetric digesters were developed using the commercial COMSOL 5.5 Multiphysics software, as shown in Fig. 2.

2.2 Assumptions for Developed CFD Model

AD is a complex process composed of many physical, chemical, and biological sub-processes. The AD modelling is governed by the conservation of mass, momentum, energy, and species transport equations integrated with the biochemical reactions model. The following assumptions are required for the developed model:

- Carbohydrates decompose into glucose (monosaccharides) in the hydrolysis process.
- Glucose is metabolized into butyric acid (a VFA) in the acidogenesis process.
- Butyric acid is degraded into acetic acid (acetate) during the acetogenesis process.

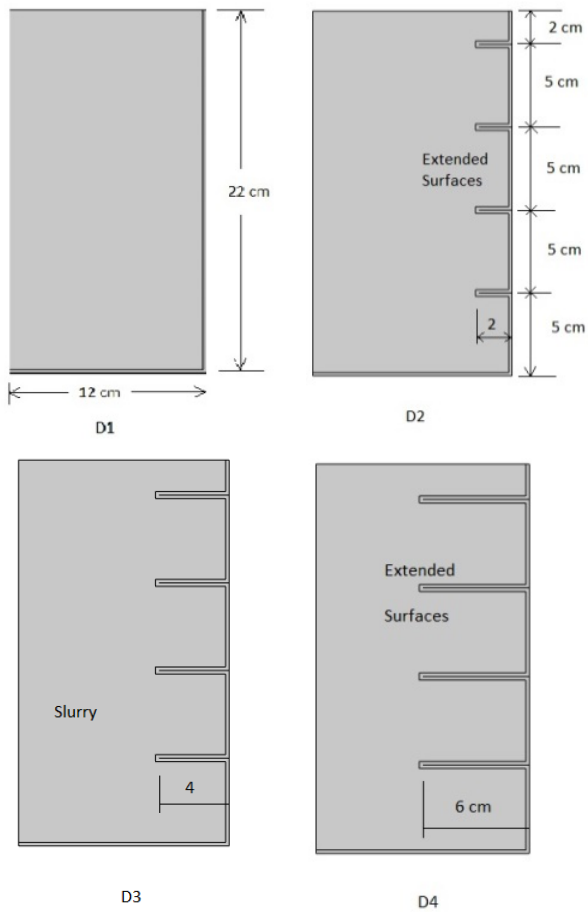


Fig. 2 The geometry of the 3D axisymmetric of the digesters shows extended surfaces.

- Methane and carbon dioxide are formed from acetic acid in the methanogenesis process.
- The model is 2D axisymmetric.
- The model is time-dependent.
- The run time is thirty days and seven days for each process except for methanogenesis, which takes nine days.
- The gravity, reduced pressure, and Boussinesq approximation are included in the fluid flow.
- The manure is single phase and phase interaction negligible.
- The generated biogas is released above the surface and does not affect the liquid manure.
- The outside walls of the digesters are adiabatic.
- The viscose dissipation is negligible.

2.3 Mathematical Model

The mathematical model includes the CFD equation solutions numerically based on the conservation laws using the commercial COMSOL 5.5 Multiphysics software code which simulates the AD in the batch digester with two multiphysics: the non-isothermal flow (laminar flow and heat transfer in fluid) and the engineering reactions (chemistry and transport of diluted species).

- Laminar flow: the behaviour of the liquid manure velocity in the digesters is governed by the momentum equation given by equation (1), which, coupled with the flow continuity equation, is provided by equation (2).

$$\rho\frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.[-pI + \mu(\nabla u + (\nabla u)^T)] + (\rho - \rho_{ref}) \quad (1)$$

$$\rho\nabla.u = 0 \quad (2)$$

u is the flow velocity (m/s), p is the local pressure (Pa), I is the unit tensor, ρ is the fluid density (kg/m^3), μ is the dynamic viscosity of the fluid (Pa.s), and g is the acceleration due to gravity (m/s^2).

- Heat transfer in fluid: the temperature distribution of the liquid manure inside the digesters is governed by the energy equation, given by equation (3).

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u.\nabla T + \nabla.(-k\nabla T) = Q \quad (3)$$

T is the fluid temperature (°K), C_p is the fluid specific heat (J/kg.K), k is the fluid thermal conductivity (W/m.K), and Q is the chemical reaction heat (heat source) (W).

- Transport of diluted species: the mole fraction of each species c_i (mol/m^3) is calculated using the species transport equation, given by equation (4).

$$\frac{\partial c_i}{\partial t} + \nabla.(-D_i\nabla c_i) + u.\nabla c_i = R_i \quad (4)$$

D_i is the diffusion coefficient for species i (m^2/s), and R_i is the reaction rate of species i by the chemical reaction (mol/m^3.s).

The physical properties of all the species can be obtained from (Yaws 2003).

2.4 Chemical Reaction Equations

AD involves four natural biological processes, represented chemically by the following chemical reaction equations, which are used to calculate the reaction rates and the species concentrations.

- Hydrolysis**:** cow manure is regarded as a carbohydrate and hydrolysis is used to reduce the manure to glucose (James N. 2019), as described by the chemical reaction equation (5) (Xiao et al. 2019).

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6 \quad (5)$$

- Acidogenesis**:** the glucose is converted into butyric acid, as given by the chemical reaction equation (6) (Yuan et al. 2014).

$$C_6H_{12}O_6 \rightarrow 4CH_3CH_2CH_2COOH + 2CO_2 + 2H_2 \quad (6)$$

- Acetogenesis**:** the butyric acid is degraded into acetic acid, as represented by the chemical reaction equation (7) (Zarei et al. 2021).

$$CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2 \quad (7)$$

- Methanogenesis**:** methane and carbon dioxide are formed from acetic acid, as given by equation (8) (Anukam et al. 2019).

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (8)$$

2.5 Reaction Rate and Heat Source Modelling

- The rate of reaction can be calculated using equation (9):

$$r_j = k_j^f \prod_{iereact} c_i^{-vij} \quad (9)$$

where C_j is the concentration of species (mol/m^3), v_{ij} is the stoichiometric coefficient, and k_j^f is the forward reaction

rate constant (s^{-1}) and can be computed using the Arrhenius expression, as shown by equation (10) (DaCosta and Fan 2012).

$$k^f = A^f \left(\frac{T}{T_{ref}}\right)^{n^f} \exp\left(\frac{-E^f}{R_g T}\right) \quad (10)$$

where A^f is the forward frequency factor (s^{-1}), n^f is the forward temperature exponent, R_g is the ideal gas constant, and E^f is the forward activation energy (J/mol), all of which can be obtained from Azargoshasb et al. (2015), Yaws (2003) and He et al. (2021).

- The heat source in the energy equation represents the heat of the chemical reaction and can be determined from equation (11).

$$Q_j = -r_j H_j \quad (11)$$

H_j is the enthalpy of the reaction for species j and can be computed from equation (12).

$$H_j = \sum_{i \in prod} \nu_{ij} h_i - \sum_{i \in react} (-\nu_{ij}) h_i \quad (12)$$

2.6 Boundary Conditions

All the walls, bases, and extended surfaces of the digesters are not slipped (fixed wall), insulated (adiabatic), and there is no flux in the concentration of the species. The cover (top) of the digesters is the open boundary for velocity, temperature, and concentration.

3. NUMERICAL IMPLEMENTATION

3.1 Mesh Analysis

The mesh independence analysis was achieved for the four digesters (D1, D2, D3, and D4). The user-controlled mesh sequence type was predominantly triangular, and the corner refinement scaling factor was 0.25, with the minimum angle between boundaries set at 240°. There were two boundary layers, with a 1.2 stretching factor, a $2*10^{-5}$ thickness, and trimmed sharp corners with a two-layer decrement. The size of the elements calibrated for fluid dynamics was predefined as extremely fine, with a 0.05 growth rate, a 0.2 curvature factor, and one narrow region resolution.

The number of elements was 102560, 109789, 109155, and 107887, while the average element qualities were 0.9653, 0.9517, 0.9516, and 0.9528 for the digesters D1, D2, D3, and D4, respectively. The mesh element quality is typically a number between 0 and 1, with 0.0 denoting a degenerated element and 1.0 denoting the best possible element. ("COMSOL Multiphysics Reference Manual", 1998). Table (1) and Fig. 3 show the elements and quality of each digester. The mesh configuration for all digesters is shown in Fig. 4.

Table 1 Quality of the elements.

D1		D2		D3		D3	
Mesh quality	NO. of Elements	Mesh quality	NO. of Elements	Mesh quality	NO. of Element	Mesh quality	NO. of Element
0.8206	1417	0.817	1787	0.8298	2278	0.8122	2726
0.8294	1843	0.8387	2337	0.8392	2896	0.8307	3535
0.8646	2294	0.8633	2760	0.8614	3340	0.8445	3954
0.877	2721	0.8805	3159	0.8821	3735	0.8632	4356
0.8914	3868	0.8926	4209	0.8913	4663	0.8862	5251
0.8734	5311	0.904	5406	0.8982	5924	0.8869	6198
0.9321	7248	0.9296	7249	0.9259	7573	0.9252	7765
0.9594	27904	0.9352	30090	0.9343	29960	0.933	29782
0.9653	102560	0.9517	109789	0.9516	109155	0.9528	107887
0.9598	136378	0.9489	144256	0.948	143320	0.9492	142002
0.9525	189425	0.947	196437	0.9478	194623	0.9461	193085
0.9501	275646	0.9428	283065	0.9511	277915	0.9251	272969

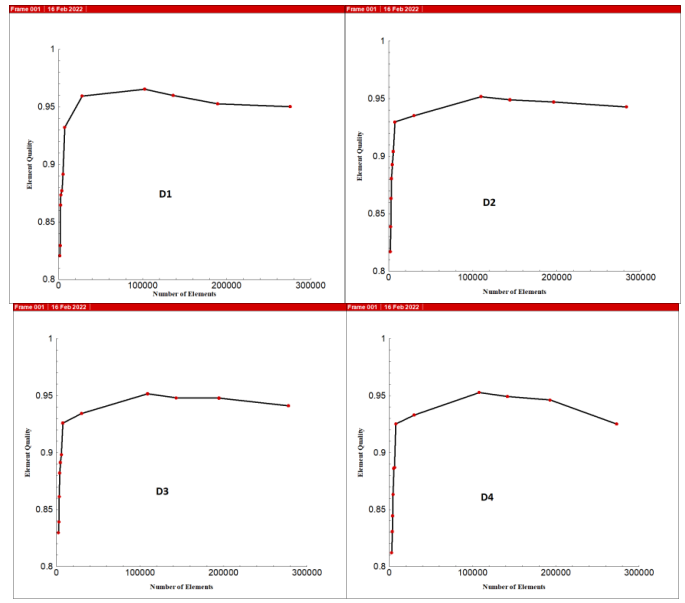


Fig. 3 The stability of the mesh.

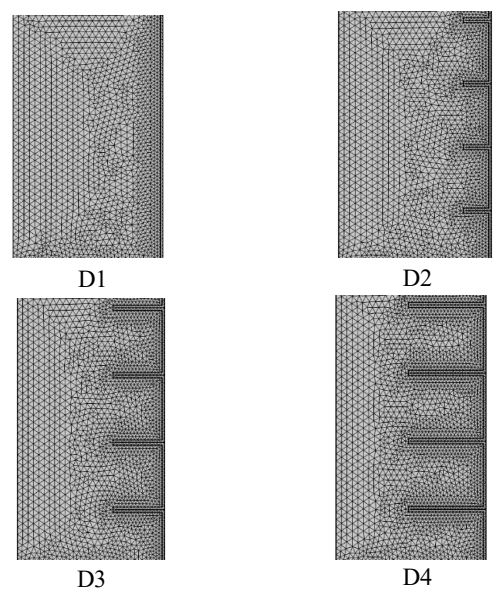


Fig. 4 The configuration of the meshes for the four digesters.

3.2 Numerical Scheme

The governing equations were solved using the finite element method, and all variables were solved using linear discretization. One study with two time-dependent steps was applied to solve each of the four AD processes of the model. Non-isothermal flow multiphysics, which involved fluid flow (the momentum equation) and heat transfer (the energy equation), was solved in the first time-dependent step, while the chemistry (the chemical reactions) and transport for the diluted species equations were solved in the second step. The velocity, pressure, and

temperature vectors coupled the momentum and energy equations. The first step of the study solves these equations, and the variables are updated, while the transport of the diluted species is solved in the second step of the study using the updated variables values from the first step. From this, the solution of the first process of AD is completed. The final updated variables value under the time-dependent (0 to 7 days) one day step time for the first process (hydrolysis) were represented as the initial values from (7 to 14 days) time-dependent for studies of the second process
(acidogenesis). The final solution of the second process is initial values for the third process (acetogenesis) of (14 to 21days) time depended while the time depended on the fourth process (Methanogenesis) of the AD starts from 21 days, which final solution of the third process, to 30 days also with one day step.

Each study's time-dependent solver applied user controller tolerance with 0.001 relative tolerance and nonlinear controller time stepping with backward Euler initialization. It was also fully coupled with the PARDISO algorithm using the constant Newton nonlinear method and the Jacobian update once per time step. Anderson's nonlinear acceleration method for each study should be used to accelerate convergence and reduce the solution time.

4. RESULTS AND DISCUSSION

Four series runs for the four AD processes were performed using CFD analysis to simulate the 3D axisymmetric velocity vector, temperature, and transport of species adding to the chemical reaction for each process using the commercial COMSOL 5.5 Multiphysics software. The runs were repeated for each geometry of the batch reactor to investigate the extended surfaces' influence on the AD performance's heat and mass transfer values. The results simulated four processes of anaerobic digestion. Each process is completed by another and takes seven days, except for the final process, which takes nine days. Finally, the results of the time final processes were discussed.

The results in this work describe the behaviour of the velocity vector for all AD processes for all the geometries of the half (3D axisymmetric) batch reactors, as shown in Fig. 5. The velocity distribution inside the digester results from the heat from the chemical reactions on the inside surfaces, resulting in natural convection currents. Since the reactions are either endothermic or exothermic, the heat is mapped as either heat generation or absorption on the map. From Fig. 5, the path of the velocity vector went from down to up for the hydrolysis and acidogenesis processes for digesters. However, the path flipped in the acetogenesis and methanogenesis processes, going from up to down. This occurs because the chemical reaction is exothermic for first two processes, leading to heat transfer to the inside of the reactor. For the two final processes, the chemical reaction is endothermic, leading to heat being absorbed by the reactor. The above applies to the eddies between the extended surfaces, which appear in the D3 and D4.

Fig. 6 illustrates the temperature distribution for all the AD processes for all the batch reactor geometries. From the figure, it can be seen that the temperature increased by a percent 1.6 % from D1 to D4 with the increasing extended surfaces because of the surface of the chemical reactions increment. These increments were achieved for the hydrolysis and acidogenesis processes via exothermic chemical reactions. However, the chemical reactions were endothermic for the acetogenesis and methanogenesis processes, so the temperature behaviour decreased from D1 to D4 with the extended surfaces reducing due to the decrement in the surfaces of the chemical reaction.

The first process, the hydrolysis of AD, at seven days for the four digesters' geometries is illustrated in Fig. 7. The profile of the reactant carbohydrate molar concentration drops from the boundary layers of the walls and the extended surfaces of digesters while the product glucose molar concentration profile rises from the boundary layers, as shown in Fig. 7. From Fig. 7, it was observed that the drop rate of the carbohydrate species and the rising rate of the glucose species increased by a percentage of 20 % from D1 to D4 with the increase in the extended surfaces due to the chemical reaction area increment.

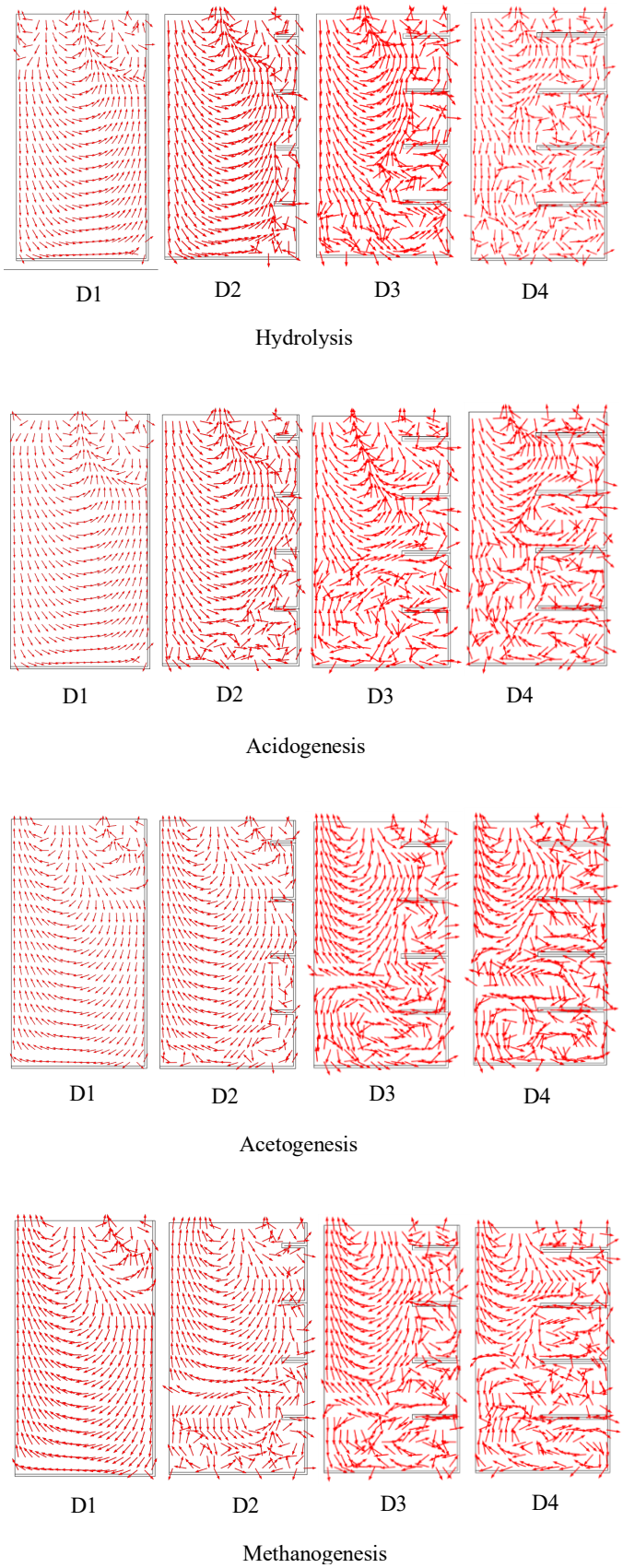
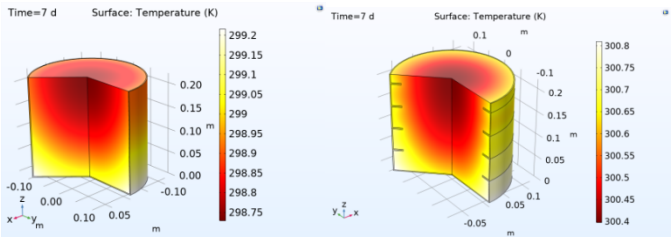
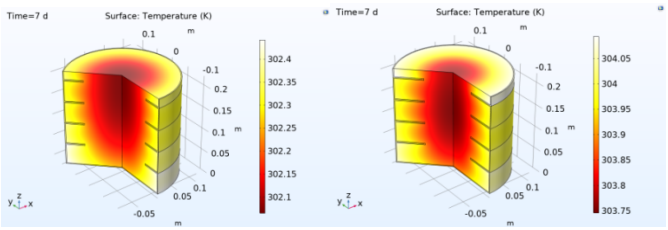


Fig. 5 The velocity vector distribution for the four AD processes for four batch reactors geometries 3D axisymmetric.

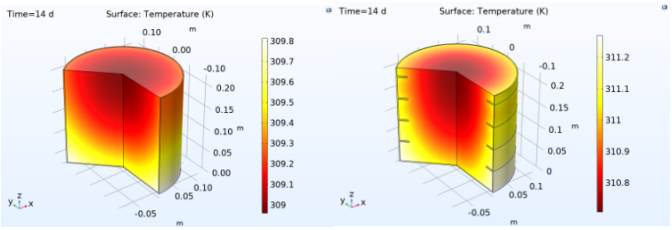


D1 D2

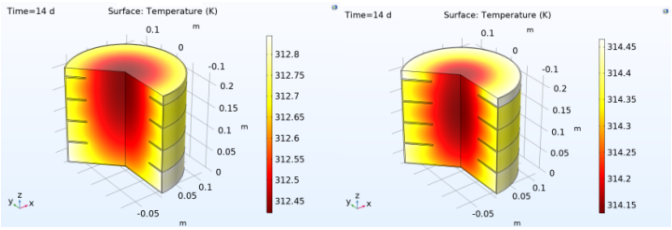


D3 D4

Hydrolysis process

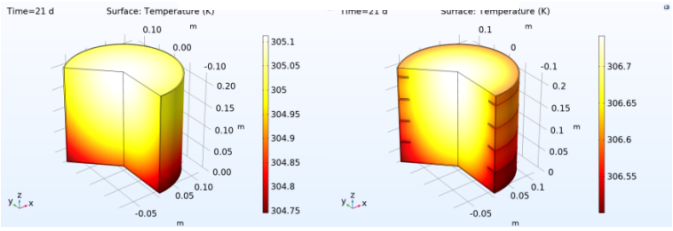


D1 D2

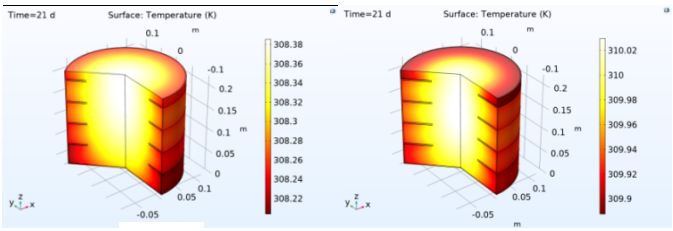


D3 D4

Acidogenesis process

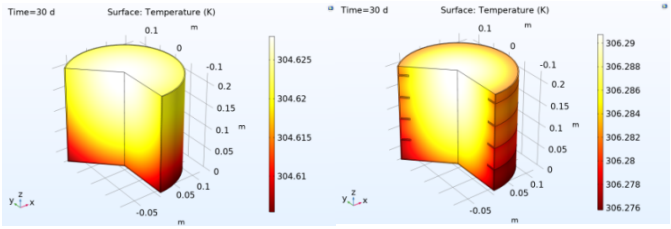


D1 D2

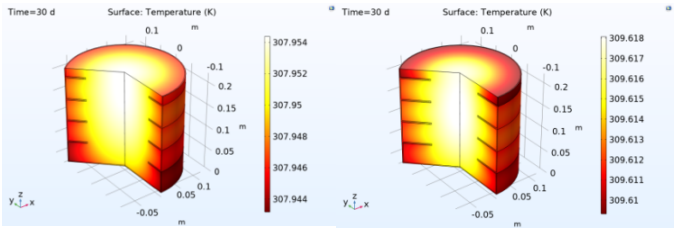


D3 D4

Acetogenesis process



D1 D2

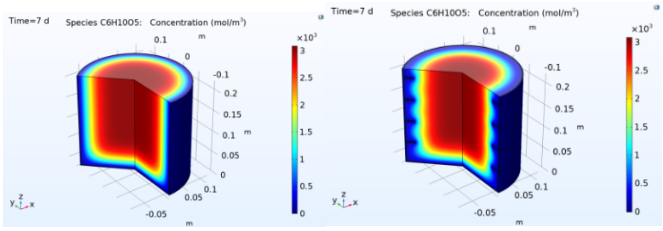


D3 D4

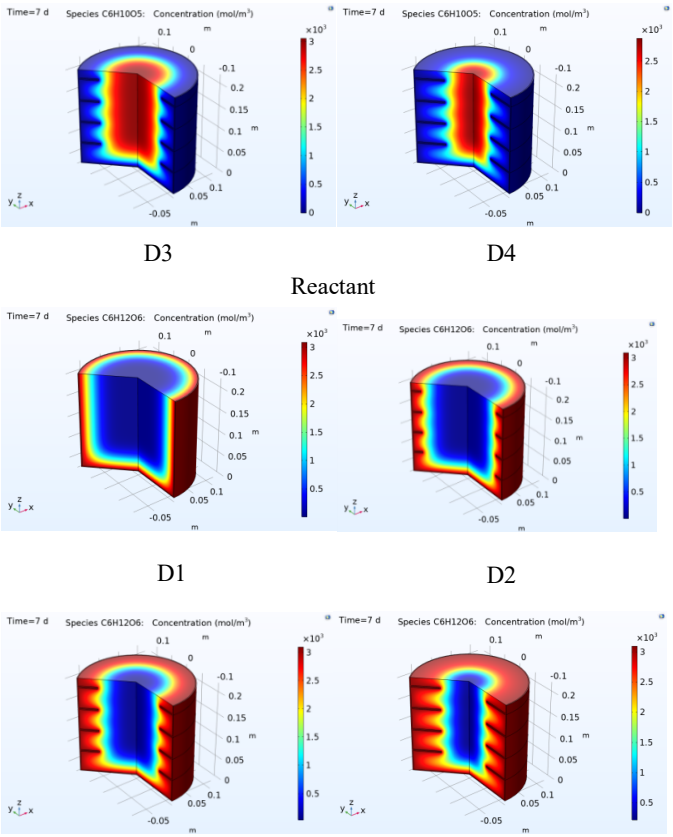
Methanogenesis process

Fig. 6 The temperature distribution for the four processes of AD for four batch reactors' geometries.

Figs. 8, 9, and 10 represent the species of the reactant and the product behaviour for all the digesters for the acidogenesis, acetogenesis, and methanogenesis processes at 14, 21, and 30 days of anaerobic digestion, respectively. Where the species profiles of the reactants of residual processes (the glucose, butyrate, and acetate for the acidogenesis, acetogenesis, and methanogenesis processes, respectively) are dropped from the boundary layers, but the product species profiles of these processes (the butyrate, acetate, and methane for the acidogenesis, acetogenesis and methanogenesis processes, respectively) arise from boundary layers. The drop and rise rates of the species reactants and products for AD's acidogenesis, acetogenesis, and methanogenesis processes depended on the chemical reaction surface area. The extended surfaces of the digesters increased from D1 to D4, leading to the species molar concentration increments of 49 %, 50 % and 78 % for the glucose, butyrate, and acetate products for the acidogenesis, acetogenesis, and methanogenesis processes, respectively shown in Figs (8), (9), and (10).



D1 D2



D3 D4

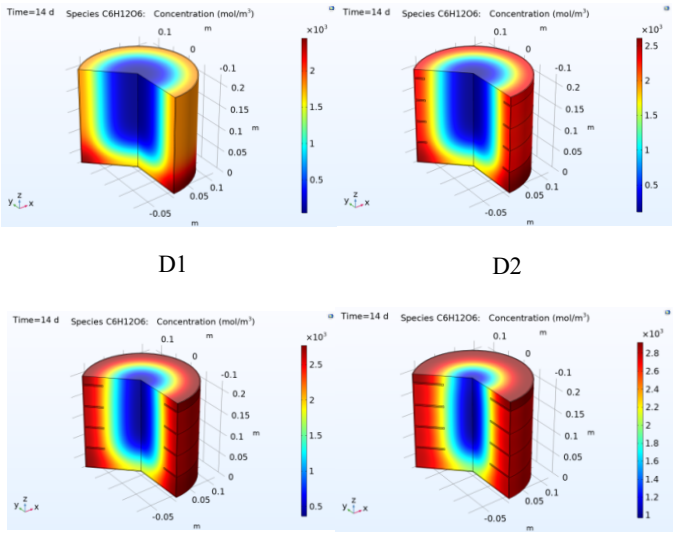
Reactant

D1 D2

D3 D4

Product

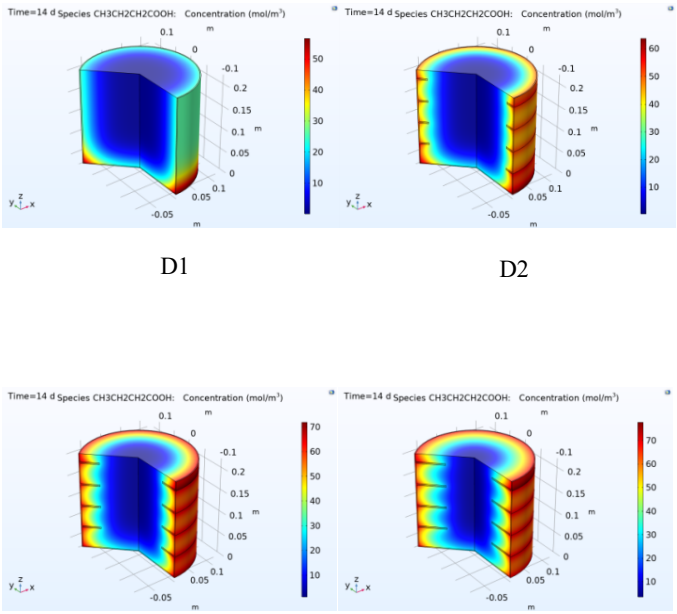
Fig. 7 The molar carbohydrate and glucose concentration behaviour for four digesters at the final hydrolysis process of AD at seven days.



D1 D2

D3 D4

Reactant

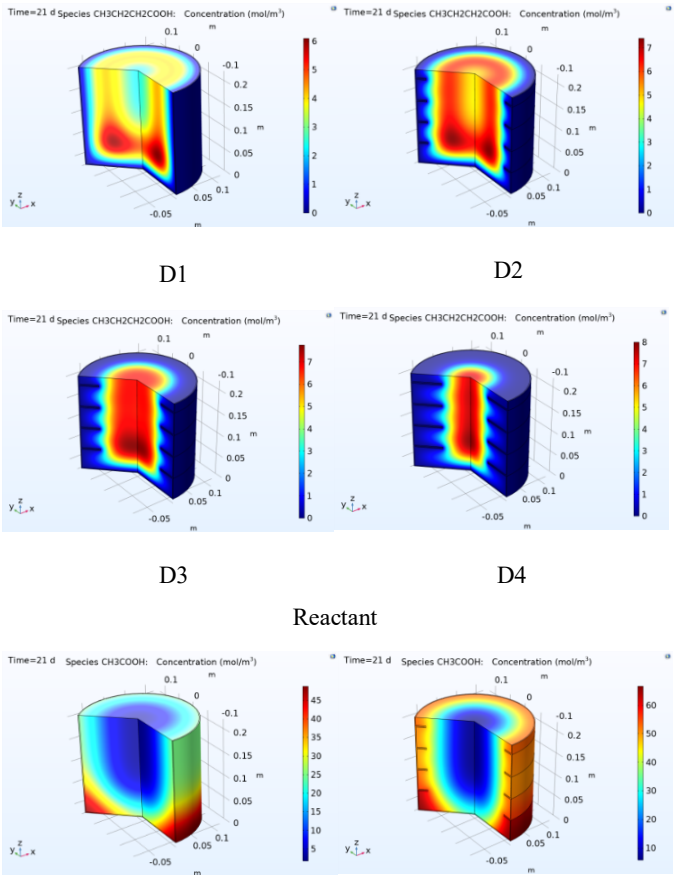


D1 D2

D3 D4

Product

Fig. 8 The molar concentration profile of glucose and butyrate for the four digesters at the final acidogenesis process of AD at 14 days.

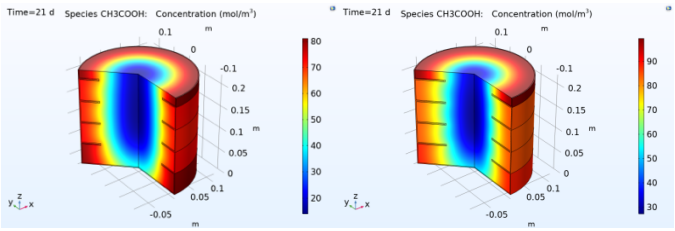


D1 D2

D3 D4

Reactant

D1 D2



D3 D4

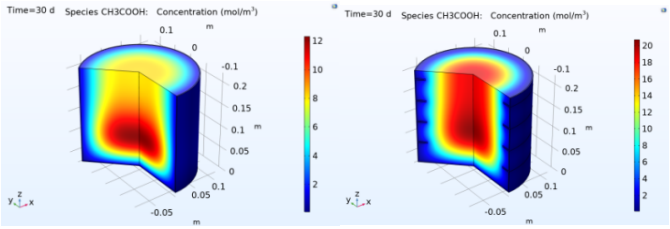
Product

Fig. 9 The molar concentration profile of butyrate and acetate for the four digesters at the final acetogenesis process of AD at 21 days.

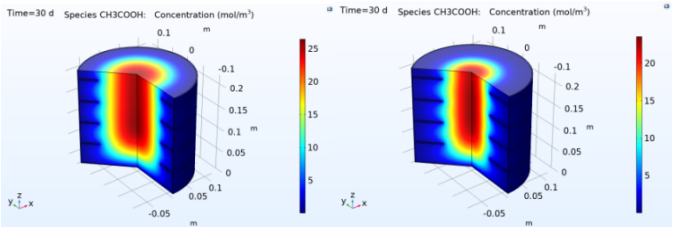
4.1 Validation of the Simulation Results

Due to the novelty of this work, the model cannot be verified by the current literature models. Therefore, the validation for the simulation results does not exist, and the validation of the sub-model of the D1 numerical results can be performed individually with experimental works.

The mole concentration average of the butyric acid for the acidogenesis and acetogenesis processes of AD was validated with the experimental work of Li, Jha, and Bajracharya (2014), which used cow dung as substrate with a 2.5 L effective volume batch anaerobic digester for 63 days under a mesophilic temperature of (35 ºC) with the mean absolute percent error (MAPE 5.8 %), as shown in Fig. 11-a. In comparison, the average acetic acid mole concentration, shown in Fig. 11-b, of the acetogenesis process of AD, compared with Komemoto et al. (2009), which used food waste as substrate, had a 2L effective volume batch digester for 22 days under mesophilic temperature (35 ºC) and an 8.4 % MAPE between them.

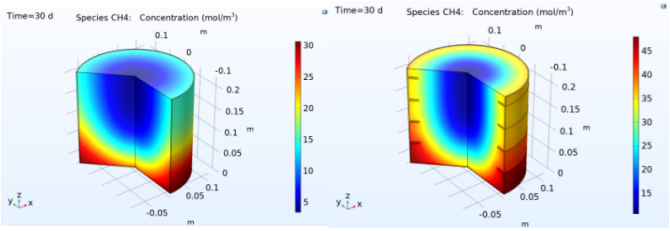


D1 D2

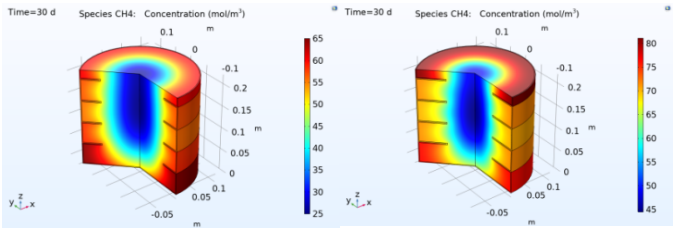


D3 D4

Reactant



D1 D2

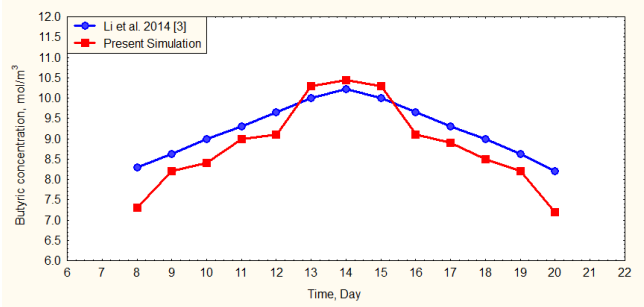


D3 D4

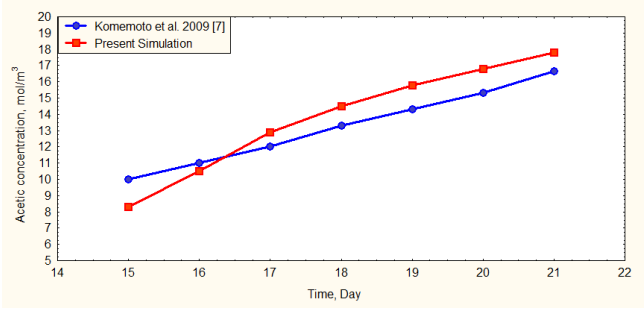
Product

Fig. 10 The molar concentration profiles of acetate and methane for the four digesters at the final methanogenesis process of AD at 30 days.

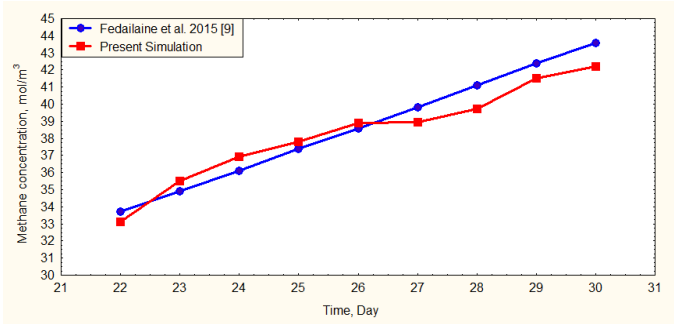
Fig. 11-c showed 1.9 % MAPE of the comparison of methane mole concentration average evolution against the modelling of Fedailaine et al. (2015), which used organic waste as substrate had a 10 L volume digester for 80 days under mesophilic conditions at the methanogenesis process of anaerobic digestion.



(a) Validation of butyric mole concentration against the Li, Jha, and Bajracharya (2014) experimental work.



(b) Validation of acetic mole concentration against the Komemoto et al. (2009) experimental work.



(c) Validation of methane mole concentration against the Fedailaine et al. (2015) modelling

Fig. 11 Comparison of the concentration distribution between the simulation results against experimental literature works.

5. CONCLUSIONS

The purpose of this paper is to present the CFD simulation with a chemical reaction model of AD processes to investigate the influence of different horizontal circular extended surface areas inside the batch reactors on AD and methane production performance.

The simulation results show that the manure's velocity distribution inside the digesters depends on the chemical reaction heat that produces natural convection currents. The chemical reaction is either endothermic or exothermic; thus, there is either heat generation or heat absorption. The chemical reactions of AD's hydrolysis and acidogenesis processes are exothermic, while the acetogenesis and methanogenesis processes are endothermic.

The chemical reaction occurs on the surface area and the horizontal circular extended surfaces. The reaction rate and the chemical reaction heat increase as the extended surface area increases, and the heat and all species' behaviour start from surface boundary layers.

The temperature profiles, the reactants' species, and the products for AD processes depend on the extended surface area. Therefore, they are at a minimum for the D1, which had no extended surfaces, and at a maximum for the D4, which had the maximum extended surfaces.

The maximum performance can be obtained from the D4 because the maximum methane molar concentration is obtained due to the maximum surface area. The simulation results are compared to current experimental results and are in good agreement.

CONFLICT OF INTEREST

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

NOMENCLATURE

Abbreviations

AD	Anaerobic Digestion.
CFD	Computation Fluid Dynamics.
MAPE	Mean Absolute Percent Error.
VFA	Volatile fatty acid.

Symbols

A^f	Forward frequency factor, s^{-1}
c	Mole fraction, mol/m^3
C_p	Specific heat, J/kg.K
D	Diffusion coefficient, m^2/s
E^f	Activation energy, J/mol
g	Gravity acceleration, m/s^2
h	Enthalpy of reaction, KJ/Kmol
k	Thermal conductivity, W/m.K
k^f	Forward reaction rate constant, s^{-1}
I	Unit tensor
n^f	Forward temperature exponent
p	Pressure, Pa
Q	Heat source, W
R	Rate of reaction, $mol/m^3.s$
R_g	Ideal gas constant
r	Rate of reaction, $mol/m^3.s$
T	Temperature, K
t	Time, s
u	Velocity, m/s

Greek Symbols

ρ	Density, kg/m^3
μ	Viscosity, Pa.s
ν	stoichiometric coefficient

Subscripts

i	Tensor
j	Species
ref	Reference

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