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Fuzzy C-means Modeling for Shell and Tube Heat Exchanger

B.Dinesh
Department of Instrumentation Engineering,
Annamalai University

E.Sivaraman
Department of Instrumentation Engineering,
Annamalai University

ABSTRACT

A shell and tube heat exchanger is a class of heat exchanger designs seen most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications. As its name implies, this type of heat exchanger consists of a shell (a large pressure vessel) with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. In this paper, the mathematical modelling of Shell and tube heat exchanger is developed and transfer function is obtained using process reaction curve method. The PID controller for a shell and tube heat exchanger is designed using Z-N tuning method. The shell and tube heat exchanger is modeled using fuzzy c-means algorithm (FCM) and its output is compared with thatof actual shell and tube heat exchanger output.

Keywords

PID, Fuzzy C-means algorithm, clustering

1. INTRODUCTION

A heat exchanger is a piece of equipment built for efficientheat transfer from one medium to another. Heatexchangers are devices that facilitate efficient heat transferbetween two media, thereby changing the temperaturedistribution of the two mediums when they are in direct orindirect contact [1]. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment. A heat exchanger is specialized device that assists in the transfer of heat from one fluid to other. In some cases, a solid wall may separate the fluids and prevent them from mixing. There are two primary flow arrangements in heat exchanger: counter-flow and parallel-flow. In Counter current mode, the hot fluid enters from one end of the exchanger and the cold fluid from the opposite end. In Co-current (Parallel) mode the flow of the hot and the cold fluid is taking place in the same direction in this case. Due to nonlinear nature, shell and tube heat exchanger system is hard to model and control using conventional methods. In this paper, an average transfer function is obtained by giving positive and negative step changes in cold water inlet flow rate[3]. The conventional PID controller is designed and simulated. From the simulation studies, it is found that PID controller gives unsatisfactory performance. To improve the performance of PID controller FCM based forward model is developed and implemented for a shell and tube heat exchanger [5].

2. PROCESS DESCRIPTION

Shell and tube heat exchanger in their various construction modifications are probably the most widespread and commonly used basic heat exchanger configuration in the process industries. They provide a comparatively large ratio of heat transfer area to volume and weight and are easy to manufacture in a large variety of sizes and flow configurations. They can operate at high pressure and their construction facilitates disassembly for periodic maintenance and cleaning. A shell and tube heat exchanger consists of a bundle of tubes enclosed within a cylindrical shell. One fluid flows through the tubes and second fluid flows within the space between the tube and the shell. Heat is thus transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. They can further be classified according to their flow arrangement. Most shell-and-tube heat exchangers are 1, 2, or 4 pass designs on the tube side depending upon the number of times the fluid in the tubes passes through the fluid in the shell.

2.1 MATHEMATICAL MODELING OF SHELL AND TUBE HEAT EXCHANGER

Fig.1 shows the two different heat exchanger sections namely shell and tube. These sections are further divided into control volumes. The following assumptions were made while designing the mathematical model of shell and tube heat exchanger. The control volumes are small and assumed to have a constant temperature. The heat exchanger is insulated and there is no heat loss from the heat exchangerto the surrounding. Rate of energy stored in the control volume is equal to the rate of gain of energy from the neighboring control volume.

The energy balanceequation on the shell control volume is given by

$$\frac{\rho_s c_s v_s}{N} * \frac{dT_{co}}{dt} = \dot{m}_s c_s (T_{ci} - T_{co}) + \frac{h_s A_s}{N} (T_{ho} - T_{co})$$

(1)

The energy balanceequation on the shell control volume is given by

$$\frac{\rho_t c_t v_t}{N} * \frac{dT_{ho}}{dt} = m_t c_t (T_{hi} - T_{ho}) + \frac{h_t A_t}{N} (T_{co} - T_{ho})$$

(2)

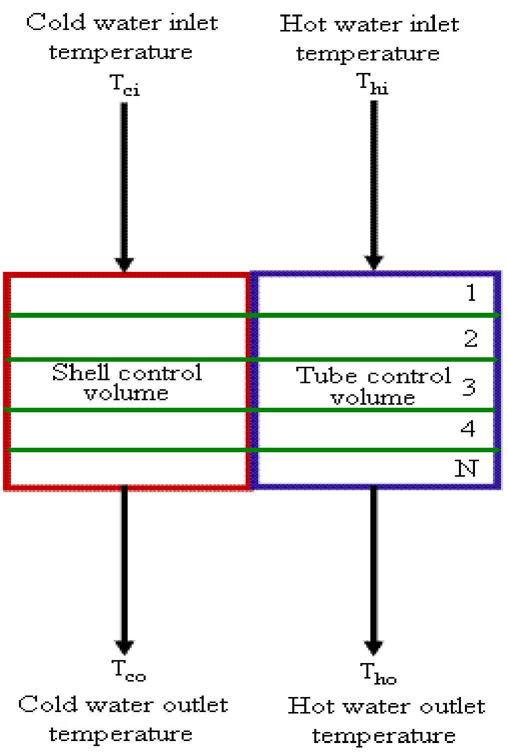

Fig 1. Shell and Tube sections of a Heat Exchanger.

Table.1 Input values for the heat exchanger mathematical model.

Inputs	**value**	**Units**
Density of water (ρ_s, ρ_t)	1000	Kg/m^3
Specific Heat Capacity of water (c_s, c_t)	4230	J/kg ^{o}C
Shell Heat Transfer Area (A_s)	0.281	m^2
Tube Heat Transfer Area (A_t)	0.253	m^2
Shell side volume (v_s)	2.62 X 10-4	m^3
7.Xube side volume (v_t)	1.43 X 10-4	m^3
Heat transfer coefficient of Shell (h_s)	2162	W/m^2 ^{o}C
Heat transfer coefficient of Tube (h_t)	2162	W/m^2 ^{o}C
Mass flow rate of cold water ($\dot{m}_s$)	0 – 0.11	Kg/s
Mass flow rate of hot water ($\dot{m}_t$)	0.0282	Kg/s
Cold water inlet temp (T_{ci})	33	^{o}C
Hot water inlet temp (T_{hi})	55	^{o}C
Number of control volume (N)	10	N/A

2.2.EXPERIMENTAL SET-UP

The shell and tube heat exchanger contains of 37 copper tubes of 750 mm length with a single pass arrangement. The two fluid streams can be arranged both in co-current and counter current fashion. The experiment is carried out using water as a single phase medium.In the process tank water is heated to a particular operating temperature. The hot fluid (water) then flows from the process tank and passes through the tube-side of the heat exchanger. Cold fluid (water) flows from the reservoir tank into the shell side of the heat exchanger. The disturbance tank is provided to study the performance of designed controllers for disturbance rejection. There are two thyristor drives that regulate the voltage and current to the heaters in order to regulate the temperature of the water in process and disturbance tank. The cold and hot water inlet flow to the shell and tubes respectively are manipulated using pneumatic control valves.The experiment is carried out in co-current mode. The hot water outlet temperature is considered as the controlled variable whereas the cold water flow rate to the shell side is treated as the manipulated variable. The flow rate of the hot water is treated as disturbance variable. The hot water inlet temperature is maintained with ± 0.5^{0}C variation using an inbuilt digital PID controller. The cold water is supplied at the room temperature. The inlet and outlet temperatures of the shell and tube side fluid are measured using the RTDs. A differential pressure transmitter (DPT) is used to measure the cold water flow rate.The inlet flow of the cold water can be varied in the range of 0-350 LPH and that of hot water between 0-250 LPH. All the sensors and interfaced with a 16 bit data acquisition system (Advantech ADAM 5000 series hardware). A PC is used to log the data and also perform the functions of the controller. The process parameters are obtained from real time using MATLAB scientific package and the communication standard used is RS232.

3. PROCEDURE FOR OBTAINING PROCESS PARAMETERS

The process reaction curve can be obtained by giving a step change in the manipulated variable. It is one of the widely followed process identification technique and this method is used for identifying parameters of the shell and tube heat exchanger at each region. For each of these regions a step change in cold water inflow rate is given in both positive and negative directions and the corresponding reaction curves are obtained as shown in Fig.2.Process reaction curve to obtain the transfer function. The transfer functions obtained are tabulated in Table 2. Using average transfer function, the controller parameters are obtained. The Ziegler–Nichols rule often leads to a rather oscillatory response to set point changes. According to Zeigler-Nichols tuning, the controller parameters are obtained and tabulated in Table 3.

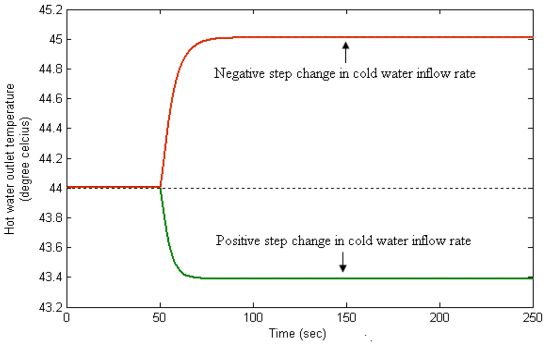

Fig.2 Process reaction curve for region1.

Table.2 Average Transfer function

Region	**Process Gain (°C/LPS)**	**Time constant(sec)**	**Dead Time (sec)**
Region I (43-45 °C)	-40.5101	0.5022	0.1123
Region II (45-47 °C)	-106.1222	0.7314	0.1298
Region III (47-49 °C)	-201.8863	0.9626	0.1395

Table.3 Process parameters of PID controller for Shell and tube heat exchanger

Region	Proportional gain	Integral gain	Derivative gain
Region I (42-45 °C)	-0.1325	-0.5899	2.3597
Region II (45-47 °C)	-0.0637	-0.2454	0.9845
Region III (47-49 °C)	-0.0410	-0.1469	0.5878

The simulations are carried out using PID controller parameters as tabulated in Table 3. The responses are obtained as shown in Fig.3, Fig.4, and Fig.5 respectively.

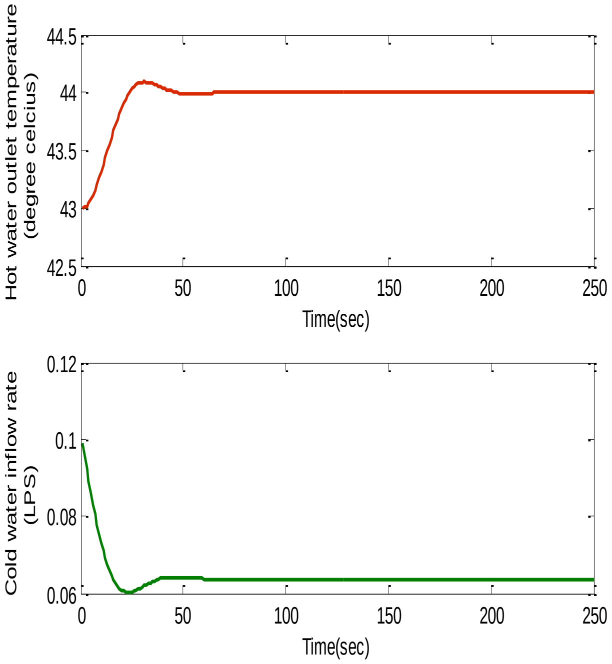

Fig.3 Servo Response of Shell and tube heat exchanger with PID controller for the operating point of 44(Region I)

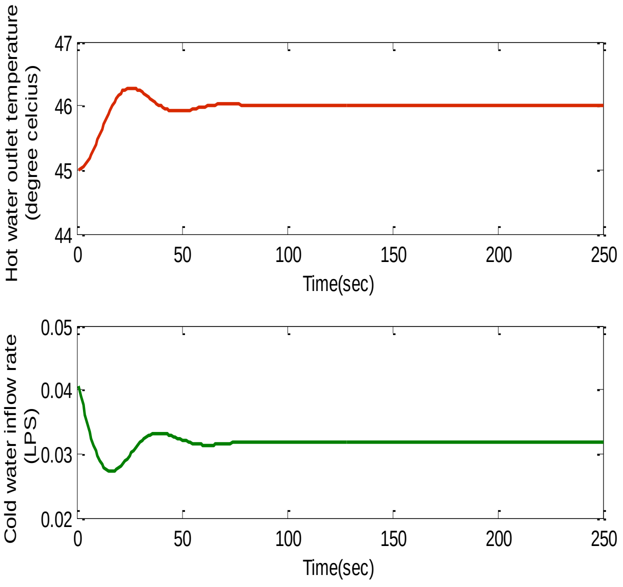

Fig.4 Servo Response of Shell and tube heat exchanger with PID controller for the operating point of 46(Region II)

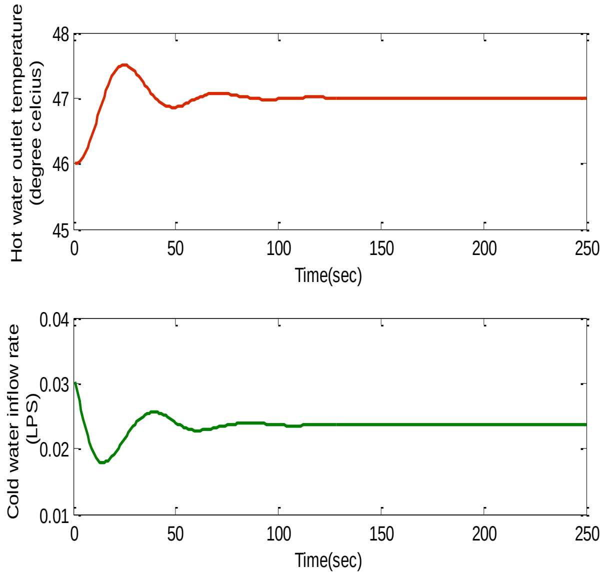

Fig.5 Servo Response of Shell and tube heat exchanger with PID controller for the operating point of 47(Region III)

4. FUZZY C-MEANS ALGORITHM

Data clustering is the process of dividing data elements into classes or clusters so that items in the same class are as similar as possible, and items in different classes are as dissimilar as possible. Depending on the nature of the data and the purpose for which clustering is being used, different measures of similarity may be used to place items into classes, where the similarity measure controls how the clusters are formed. Some examples of measures that can be used as in clustering include distance, connectivity, and intensity. In hard clustering, data is divided into distinct clusters, where each data element belongs to exactly one cluster. In fuzzy clustering (also referred to as soft clustering), data elements can belong to more than one cluster, and associated with each element is a set of membership levels. These indicate the strength of the association between that data element and a particular cluster. Fuzzy clustering is a process of assigning these membership levels, and then using them to assign data elements to one or more clusters

Let X= $\{x_1 \ldots x_j \ldots. x_n\}$ be the set of n objects and V=$\{v_1 \ldots v_j \ldots v_n\}$ be the set of centroids where $x_j \in R^m, v_i \in R^m$ and $v_i \in X$.The FCM provides a fuzzification of the HCM. It partitions the X into c clusters by minimizing the objective function.

$$J = \Sigma_{j=1}^{n} \Sigma_{i=1}^{c} (\mu_{ij})^{m1} \| x_j - v_i \|^2$$
(3)

Where $1 \le m_1 < \infty$ is the fuzzifier, v_1 is the ith centroid corresponding to cluster β β_i, $\mu_{ij} \in [0,1]$ is the probabilistic membership of the pattern x_j to cluster β_i and ‖ . ‖ is the distance norm, such that

$$v_i = \frac{1}{n} \Sigma_{j=1}^{n} (\mu_{ij})^{m1} x_j, \text{Where}$$
$$ni = \Sigma_{j=1}^{n} (\mu_{ij})^{m1} \qquad (4)$$

$$\mu_{ij} = \left(\Sigma_{k=1}^{c} \left(\frac{d_{ij}}{d_{kj}}\right)^{\frac{2}{m1-1}}\right)^{-1} \text{Where}$$
$$d_{ij}^2 = \| x_j - v_i \|^2 \qquad (5)$$

Subject to $\Sigma_{i=1}^{c} \mu_{ij} = 1, \forall j$, and $0 < \Sigma_{j=1}^{n} \mu_{ij} < n, \forall i$

The process begins by randomly choosing c objects as the centroids of the c clusters. The memberships are calculated based on the relative distance of the object x_j to the centroid. After computing the membership of all the objects the new centroids of the cluster are calculated. The process stops when the centroids stabilize. That is the centroids from the previous iteration are identical to those generated in the current iteration.

In the FCM,the memberships of an object are inversely related to the relative distance of the object to the cluster centroids. In effect, it is very sensitive to noise and outliers.In addition, from the standpoint of “compatibility with the centroid”, the membership of an object x_j in a cluster β_i should be determined slowly by how close it is to the mean v_i of the class and should not be coupled with its similarity with respect to other classes.

To alleviate this problem, Krishnapuram and Keller introduced the PCM, where the object can be formulated as

$$j = \sum_{i=1}^{c}\sum_{j=1}^{n}(v_{ij})^{m2} \| x_j - v_i \|^2 + \sum_{i=1}^{c}\sum_{j=1}^{n}(1 - v_{ij})^{m2} \quad (6)$$

Where $1 \le m_2 < \infty$ is the fuzzifier,and η_i represents the scale parameter. The membership matrix v that is generated by the PCM is not a partition matrix in the sense that is not satisfies the constraint

$$\sum_{i=1}^{c} v_{ij} = 1$$

The update equation v_{ij} is given by

$$v_{ij} = \frac{1}{1 + D} \quad (7)$$

Where $D = \{\frac{\| x_j - v_i \|^2}{\eta_i}\}^{\frac{1}{(m2-1)}}$ subject to $v_{ij} \in [0,1], \forall i, j; 0 < \sum_{j=1}^{n} v_{ij} \le n, \forall i$ .The scale parameter η_i represents the zone of influence or size of the cluster β_i .The update equation for η_i is

$$\eta_i = K.\frac{P}{Q} (8)$$

$$P = \sum_{j=1}^{n} (V_{ij})^{m2} \| x_j - v_i \|^2$$

$$Q = \sum_{j=1}^{n} (V_{ij})^{m2}$$

Typically is chosen to be one. In each iteration, the updated value of V_{ij} depends only on the similarity between the object and the centroid. The resulting partition of the data can be interpreted as a possible partition, and the membership values may be interpreted as degrees pf possibility of the objects belonging to the class the compatibilities of the object with centroids. Updating of the means proceeds exactly the same way as in the case of FCM.

4.1 GENERATION OF INPUT-OUTPUT DATA FOR MODELING OF STHE

The perturbed cold water inflow is given to the shell and tube heat exchanger mathematical model and the corresponding hot water outlet temperature values are obtained by simulation are shown in Fig.4.1 and 4.2 respectively. The range of perturbed cold water inflow rate and the corresponding hot water outlet temperature values are given in Table 4.1.

Table.3 Data set for training the STHE model.

Input Vector		**Output Vector**	
Cold water inflow rate (C_{in})	[0.02-0.09 LPS]	Hot water outlet temperature (T_{ho})	[43.25°C – 47.5°C]

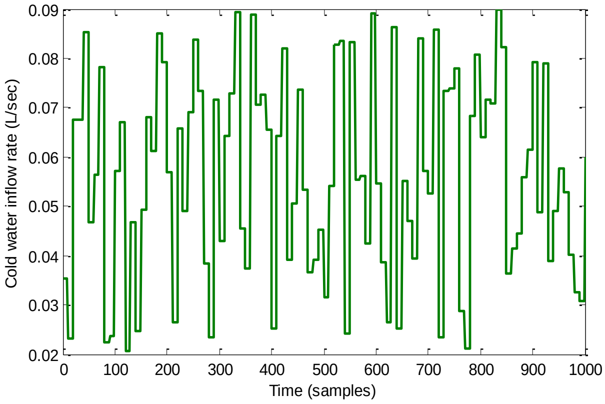

Fig.6 Random **input (C_{in}) to the STHE**

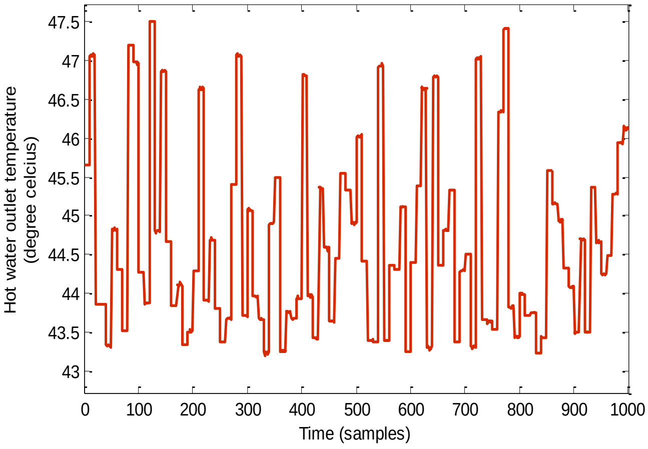

Fig.7 Response of T_{ho} for random C_{in}.

5. SIMULATION RESULTS WITH FCM ALGORITHM

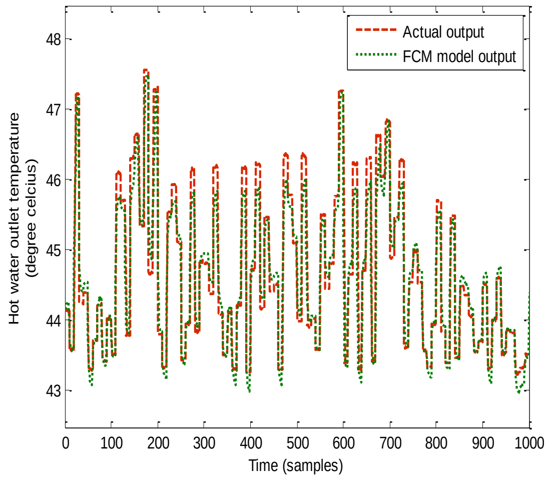

Fig.8. Comparison of simulated FCM model output and actual output of STHE.

The Fig.8 shows the FCM model output matches the actual output of shell and tube heat exchanger.

6. 6. CONCLUSION

In this work, the mathematical modelling of Shell and tube heat exchanger is developed and the transfer function model of shell and tube heat exchanger is obtained for different regions. The PID controller for a shell and tube heat exchanger is designed using Z-N tuning method. The fuzzy forward model of shell and tube heat exchanger is developed based on FCM algorithm. The obtained model output is compared with that of actual shell and tube heat exchanger output.

7. REFERENCES

[1] Subhransu Padhee., 2011 Performance Evaluation of Different Conventional and Intelligent Controllers for Temperature Control of Shell and Tube Heat Exchanger System",MS Thesis Thapar University, India.

[2] Sivakumar, P., Prabhakaran, D.,Kannadasan, T.,2012 Temperature Control of Shell and Tube Heat Exchanger Using Intelligent Controllers-Case Study. International Journal of Computational Engineering Research, Vol. 2 Issue. 8,pp 285-291.

[3] Saranya, E.,Arulselvi, S., 2013Design and Simulation of Conventional and Intelligent Controllers for Temperature Control Of Shell and Tube Heat Exchanger System, International Journal of Recent Technology and Engineering, Volume-2, Issue-3,pp.4-11.

[4] Rajasekaran, S., Kannadasan, T.2010 ASimplified Predictive Control for a Shell and Tube Heat Exchanger, International Journal of Engineering Science and Technology, Vol. 2 (12), pp.7245-7251.

[5] Swapnaneel Sarma, Das, D.H., 2012 CFD Analysis of Shell and Tube Heat Exchanger using triangular fins for waste heat recovery process, Engineering Science and Technology: An International Journal, Vol.2, No.6,pp.1033-1041.

[6] James C. Bezdek, Robert Ehrlich, William Full,1984 FCM: The Fuzzy c-Means Clustering Algorithm, Computers & Geosciences, Vol. 10, No. 2-3, pp. 191-203.

[7] ArunSivaram,Sainabha, M.,Ramkumar, K.2013 Parameter Identification and Control of a Shell and Tube Heat Exchanger, International Journal of Engineering and Technology, Vol 5, No 2,pp.1589-1593.

[8] Amin Hadidi, Mojtaba Hadidi, Ali Nazari, 2013 A new design approach for shell-and-tube heat exchangers using imperialist competitive algorithm (ICA) from economic point of view, Energy Conversion and Management, pp.66–74.

[9] Rajasekaran, S., Kannadasan, T.,2012 Swarm Optimization based Controller for Temperature Control of a Heat Exchanger, International Journal of Computer Applications, Volume 38, No.4, pp. 6-11.