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USE OF A NUMERICAL TECHNIQUE FOR MONITORING OF CONVECTION COEFFICIENT IN INDUSTRIAL PROCESSES

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Abstract. *Industrial processes such as fermentation, hydrogenation, oxidation, water treatment, petrochemical, among others, involve chemical, physical, thermal, electronic or mechanical phenomena that require operational quality. Therefore, the control and monitoring of processes are made from variables, such as temperature, pressure and speed of flow, measured in real time and demand robust and efficient methods. In this context, the monitoring of thermal and physical properties become fundamental and can be accomplished through determination of specific convection coefficients, study which accompanies various conditions and procedures. This work consists in application of a numerical technique for monitoring of convection coefficient in industrial processes. Associated with a thermal probe inserted into a change able flow temperature, the convection coefficient is monitored from the acquisition of temperature by two thermocouples with the same external geometry, but with both encapsulation and time constants are different. Each thermocouple is responsible for appointing a distorted and delayed temperature which can be reconstructed by an appropriate mathematical model of inverse regularization. Assuming convection about analogous in both thermocouples, numerical tests showed that the technique is effective in calculating a convection coefficient common even under sensitivity of noises.*

Keywords: *Inverse problem, convection coefficient, temperature, regularization.*

1. INTRODUCTION

Industrial processes involving heat transfer are an area of great interest of engineering by the variability applications including chemical processing, bio-heat transfer, reactors, heat exchangers, fermentation, hydrogenation, oxidation, water treatment, petrochemical and many others (Mirsephai, *et al.*, 2013; Silva Neto, *et al.*, 2007; Goldstein, *et al.*, 2002). The involved heat transfer in industrial processes may involve three phenomena: conduction, convection and radiation, and measurement techniques, monitoring and control are employed to ensure the quality and safety of the operating systems where these phenomena occur (Oliveira, *et al.*, 2006).

According Mirsephai, *et al.* (2012), Liu (2008) and Colaço and Orlande (2004), the problems of heat transfer can be divided into direct and inverse problems. The direct problems of heat transfer consist in determining the temperature distribution in a medium, where all the relevant thermophysical properties are known. By contrast, the inverse problems of heat transfer approach to determine the temperature distribution in a medium, but on the absence of data related to thermophysical properties.

The direct problems of heat transfer are known as well-posed, in other words, in the sense of Hadamard, conditions of existence, uniqueness and stability are met (Mirsephai, *et al.*, 2012, Bazánand Borges, 2009 and Colaço and Orlande, 2004). While the inverse problems of heat transfer are usually ill-posed, that is, a Hadamard conditions is not satisfied, for example, small variations in the input data cause considerable changes in the solution which would indicate a lack of stability. As consequence of this natural ill conditioning of inverse problems is that experimental mistakes neglected can be strongly amplified, corrupting completely the reconstruction of temperature. Whereas experimental errors and distortions in the temperature measurement are inevitable, special techniques, such as regularization methods must be implemented to control such problems in order to get acceptable results.

The regularization methods have emerged in the decades 50-60, being the best-known of them, the regularization of Tikhonov (Tikhonov and Arsenin, 1977). The purpose of regularization methods is change slightly the ill-posed problem in order to make it well-posed and analyze the data from this new problem well-conditioned (Bazán and Borges, 2009).

Recently, many studies on inverse problems of heat transfer have been performed (Mirsephai, *et al.*, 2012; Liu, 2008; Oliveira, *et al.*, 2006; Goldstein, *et al.*, 2002), and development of these methods occur as the progress of the mathematical theory, computer and instrumental technology and numerical techniques. So algorithms are improved, tested in numerical experiments, which have become a significant part to fundamental research and practical applications. All these actions are always implemented in the intention to improve the efficiency of such methods and precision of the solutions.

In Oliveira, *et al.* (2006) a numerical technique of signal processing was able to reconstruct in real time the temperature of the original process from a distorted signal, delayed and noisy measured by an intrusive probe. The problem formulation took into consideration thermal accumulation, convection and radiation. Numerical and experimental results have shown that the proposed technique in Oliveira, *et al.* (2006) allows reconstruction of process temperature under experimental conditions with real relatively high noise levels, but the time constant of the probe and the radiation coefficient dependent on the convection coefficient which have been determined in advance by a minimization process which is not appropriate for real-time processing, because the process of temperature reconstruction would depend on outdated information.

The objective of this work is to apply the numerical technique developed in Oliveira, *et al.* (2006) and determine a range of performance for the convection coefficient. The proposed method is the monitoring of the convection coefficient measured of the temperature by two thermocouples with the same external geometry but different time constants. Each thermocouple indicates a distorted and delayed temperature that can be reconstructed by an inverse model regularized appropriate. Assuming convection is nearly analogous in both thermocouples, the corresponding model can be used to calculate the convection coefficient common.

Numerical tests were performed and showed that the technique is effective in calculating a convection coefficient common even under sensitivity of noise, attenuating errors due from inverse problem.

2. FORMULATION OF THE PROBLEM

The strategy for monitoring the convection coefficient considers the measurement of the temperature of a flow by two thermocouples with the same external geometry but different time constants due to different sheathed, Fig. 1.

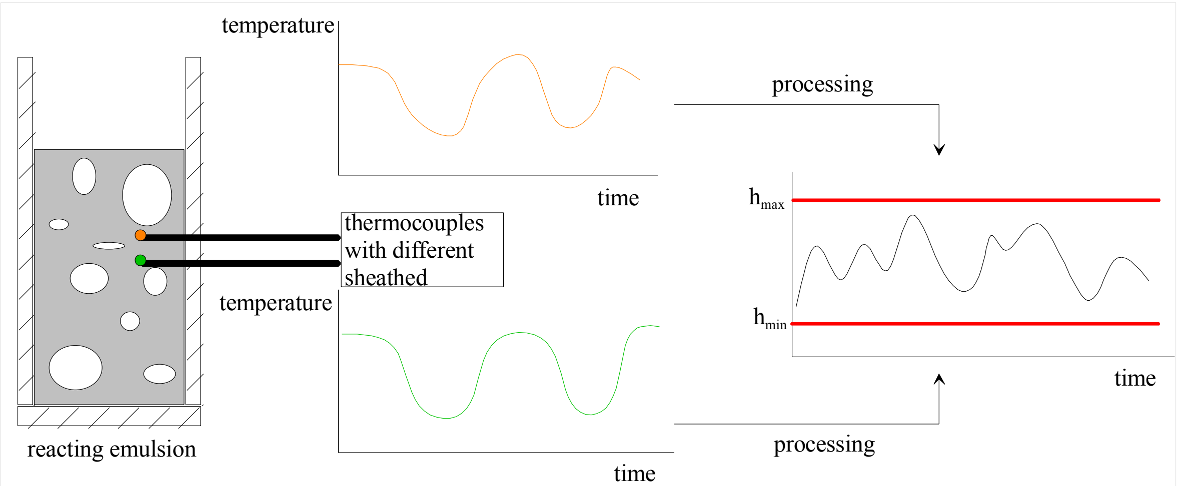

Figure 1. Strategy for monitoring of convection coefficient

Each thermocouple indicates a distorted and delayed temperature can be reconstructed by an inverse model regularized appropriate. Assuming convection is nearly analogous in both thermocouples, the corresponding model can be used to calculate the convection coefficient common.

The transduction equation of the thermocouples can be represented by Eq. (1), considering thermal accumulation and convection:

$$MC\frac{dT}{dt} - hA\left(T_\infty - T\right) = 0 \tag{1}$$

where mass M (kg), specific heat C (J/KgK), surface area of heat transfer A (m^2), convection coefficient h (W/m^{2}K) and fluid temperature or free-flowing one T_∞ (K).

Dividing Eq. (1) by hA and considering two thermocouples A and B, as:

$$\frac{M_A C_A}{hA}\frac{dT_A}{dt} - \left(T_\infty - T_A\right) = 0 \tag{2}$$

$$\frac{M_B C_B}{hA}\frac{dT_B}{dt} - \left(T_\infty - T_B\right) = 0 \tag{3}$$

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As the process temperature T_∞ is the same for both thermocouples, as:

$$T_\infty = \frac{M_B C_B}{hA}\frac{dT_B}{dt} + T_B = \frac{M_A C_A}{hA}\frac{dT_A}{dt} + T_A \tag{4}$$

then the convection coefficient can be determined by:

$$h = \frac{1}{A(T_A - T_B)}\left(M_B C_B \frac{dT_B}{dt} - M_A C_A \frac{dT_A}{dt} \right) \tag{5}$$

An immersed thermocouple in the reagent emulsion provides the temperature of the flow that will be named indicated temperature T_{ind}, then by Eq. (5) is possible to get the indicated convection coefficient relative to emulsion reagent, h_{ind}:

$$h_{ind} = \frac{1}{A(T_{indA} - T_{indB})}\left(M_B C_B \frac{dT_{indB}}{dt} - M_A C_A \frac{dT_{indA}}{dt} \right) \tag{6}$$

The Eq. (6) can be discretized in time by the method of finite difference delayed with indexes n and $n-1$ indicating that the variable refers to the times $t = n\Delta t$ and $t = (n-1)\Delta t$, and Δt step in the time. Therefore Eq. (6) can be rewritten as:

$$h_{ind} = \frac{1}{A\Delta t(T_{indA,n} - T_{indB,n})}\left(M_B C_B (T_{indB,n} - T_{indB,n-1}) - M_A C_A (T_{indA,n} - T_{indA,n-1}) \right) \tag{7}$$

According to Oliveira, *et al.*(2006) the derivative of Eq. (6) acts as a high-pass filter and thus the elements of the low-frequency signal of T_{ind} are smoothed while the high frequency elements, where there is much noise, are amplified and so there was the need to apply a regularization technique to obtain the process temperature in the real-time. Thus, get the convection coefficient from Eq. (7) is not convenient, for a range of performance for the convection coefficient would be amplified, and then require a regularization technique for such a chore. Then the regularization technique adopted in Oliveira, *et al.* (2006) that proved to be efficient to obtain the process temperature in real-time, will be applied in Eq. (7) for monitoring of convection coefficient.

The technique applied in Oliveira, *et al.*(2006) is known as the Simplified Method of Least Squares or Savitzky-Golay Filters (Savitzky and Golay, 1964), in which basic idea is to adjust a polynomial of low level N for the last $m+1$ indicated temperature and to substitute dT_{ind}/dt and T_{ind} on Eq. (6) by smoothed values obtained from this polynomial.

Following the algorithm present in Oliveira, *et al.*, (2006), $T_{smooth}(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_N x^N$ is a polynomial, where x is a support shaft centered on the last acquired temperature and oppositely oriented the time. The system formed by the polynomial must be solved by the Method of Least Squares to adjust the coefficients with the minimization scheme of error, and to get:

$$T_{ind}(n\Delta t) \cong T_{smooth}(0) = a_0 \tag{8}$$

$$\frac{dT_{ind}}{dt}(n\Delta t) \cong -\frac{dT_{smooth}}{dx}(0) = -a_1 \tag{9}$$

The values of Eq. (8) and Eq. (9) are substituted into Eq. (7) and this way, it is gotten the regularized convection coefficient from smoothed values of T_{ind}, therefore h_{reg} :

$$h_{reg} = \frac{1}{A\Delta t(a_{0A,n} - a_{0B,n})}\left(M_A C_A a_{1A,n} - M_B C_B a_{1B,n} \right) \tag{10}$$

Then, the values of the convection coefficient are updated at each iteration, and consequently a range of performance is built for monitoring.

3. RESULTS

The methodology adopted in this paper was implemented on software LabView™ from the National Instruments and tested in numerical experiments that simulated the immersion of two thermocouples in an emulsion reagent with minimum temperature of 363 K and maxim of 373 K, process convection coefficient (h_{proc}) constant at 550 W/m²K, $M = 4{,}7\times10^{-6}$ Kg/m³, $C = 3{,}8\times10^{2}$ J/KgK and $A = 3{,}14\times10^{-6}$ m², which gives a time constant for each thermocouple of $MC/hA = 1{,}03$ s, noise of 0,01 K, order of the polynomial 2 and quantity of points used to regularize equivalent to 10.

The results generated are presented in the process convection coefficient (h_{proc}), indicated convection coefficient (h_{ind}) obtained from the Eq. 7, and regularized convection coefficient (h_{reg}) obtained from the Eq. 10, these values are updated for each time step Δt.

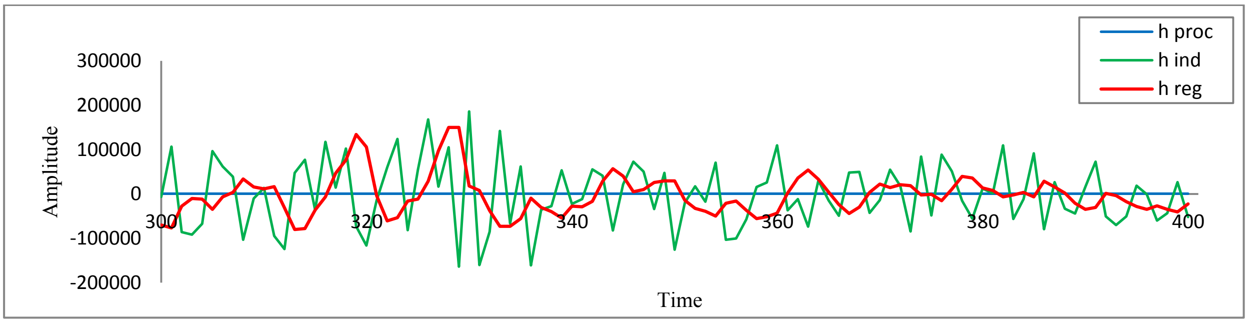

Figure 2. Convection coefficient h_{proc}, h_{ind} and h_{reg}

It is observed in Fig. 2 the h_{reg} obtained smoothed the h_{ind}, keeping the purpose of reconstructing the signal of the convection coefficient in accordance with the method which has been proposed, but it is noted the delayed signal, and this aspect is expected because of the time constant of the probe and processing time. However, the reconstruction of signal process finally introduces, randomly and low frequency, two phenomena. The first is the occurrence of discontinuity in the behavior of h_{reg} and of h_{ind} results from the difference between a_{0A} and a_{0B} (Eq. 10), $T_{ind,A}$ and $T_{ind,B}$ (Eq. 7) are very close to zero and also by the those same difference are located in the denominator of equations, as can be observed in the Fig. 3 to h_{reg} and Fig. 4 to h_{ind}.

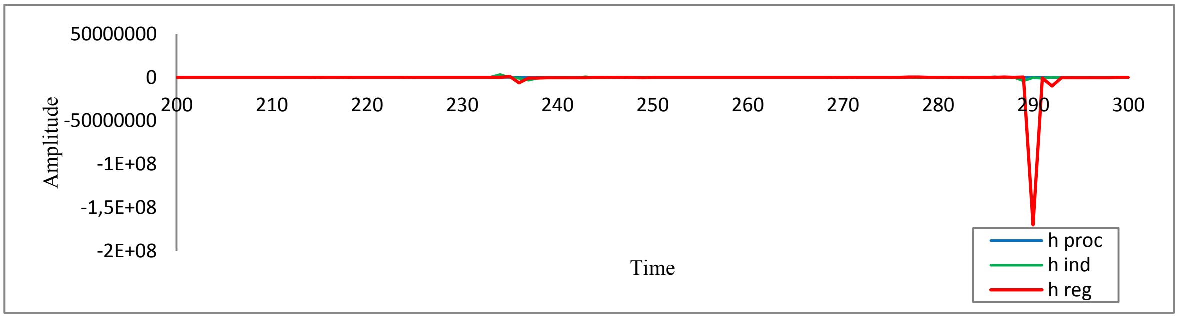

Figure 3. Discontinuance in the behavior of regularized convection coefficient

Note in Fig. 4 that even h_{ind} presenting these peaks, the h_{reg} still tries to attenuate these data, it does not follow the discontinuity and show itself efficiently from the method of regularization. In Fig 3, it is observed that only the h_{reg} submitted this characteristic.

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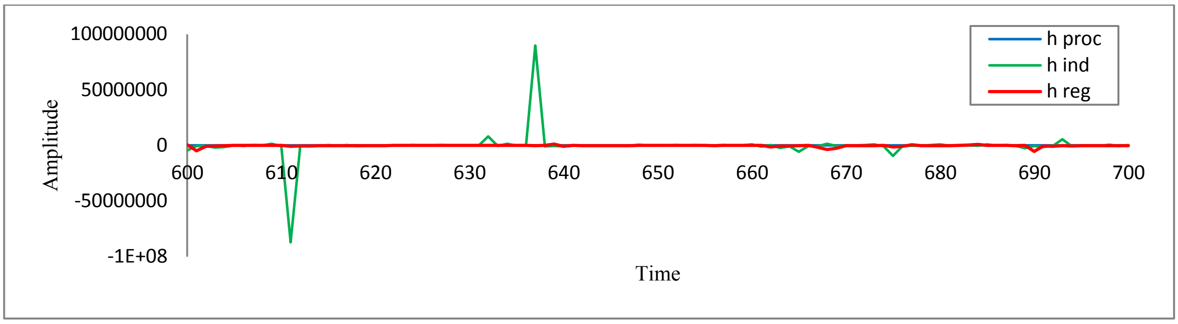

Figure 4. Discontinuance in the behavior of indicated convection coefficient

The second problem is the exceeded peaks also occur randomly and low frequency, Fig. 5. Every time the signal surpasses a certain data pattern displayed, but it does not originate from the discontinuity of at least one of h, can be said that the h_{ind} presented a signal too strong and the h_{reg} accompanied, in an attempt to attenuate it, as exemplified by the Fig. 5, but ended up exceeding the same standard of data displayed.

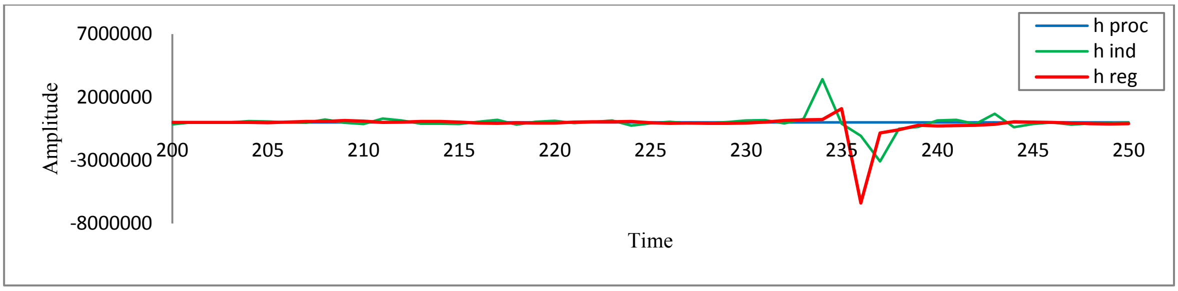

Figure 5. Peaks exceeded in the indicated convection coefficient and regularized one

The purpose to eliminate the inconvenience of the problems generated by the discontinuity and the peaks exceeded that do not characterize the convection coefficient sign and thus compromise its monitoring, some alternative control were proposed these phenomena in order to determine the best range of active convection coefficient.

Thus, through observation of the results of numerous tests, it is concluded that there are few points that exceed the range of 50000 W/m²K in absolute value for h_{reg}, therefore the h_{reg} obtained at each Δt are more stable within this range, Fig. 6. Then for values above of the previously determined limit range are controlled and receive the value of h_{proc}, highlighted in orange on Fig 7.

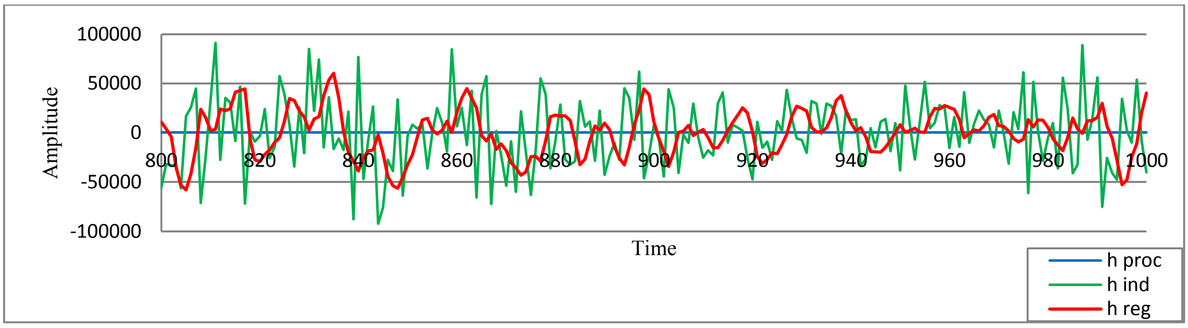

Figure 6. Adjust of indicated convection coefficient signal

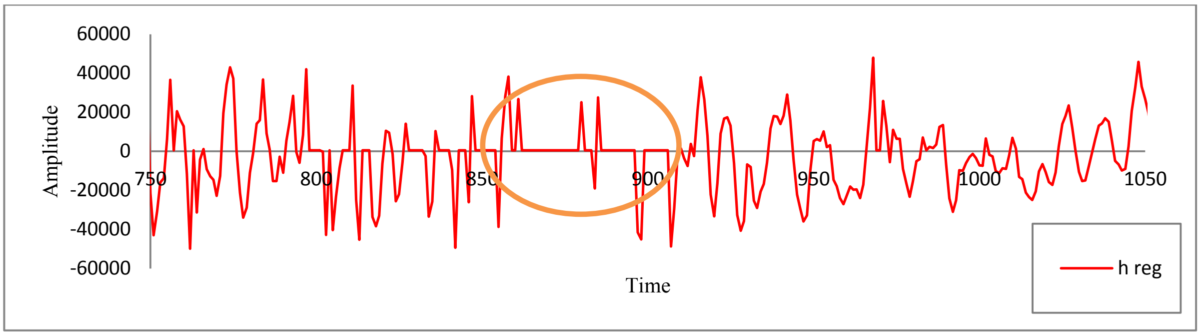

Figure 7. Control of the regularized convection coefficient

Tests were also made with different orders of the polynomial, various amounts of points and noise.

In tests in which the order of the polynomial was changed, it was noted the h_{reg} becomes unstable, extrapolating the limit range with the highest frequency. So for best results in the reconstruction of the convection coefficient are considered degree polynomial low (order is equal to two). The change in the amount of points to application of the regularization method involves changes in the graphic shape, but there was not sudden changes in the behavior of the h_{reg}, but its amplitude is smaller, which shows a monitoring stricter, but by Oliveira *et al.* (2006) it is known that the temperature reconstruction is uncharacteristic.

The algorithm was tested for different intensities of noise and for extremely small one, around 10^{-7} K, extrapolations of the signal in relation to the limit range are minimal, and still the signal stay very close to the value of h_{proc}. Regarding noise considered extremely high, above of 1 K, is required a reassessment of the value for the range limit.

4. CONCLUSION

A procedure for monitoring the convection coefficient of industrial processes has been proposed in this paper. The algorithm consists of monitoring the convection coefficient of a process from the temperature measured by two thermocouples with the same external geometry but different time constants. Each thermocouple indicates a distorted and delayed temperature that was reconstructed by a model regularized inverse appropriate. Assuming convection about analogous in both thermocouples the corresponding model was used to calculate the convection coefficient common. Through numerical experiments the methodology applied in this study proved to be efficient to delimit a range of activities for monitoring of convection coefficient under realistic noise conditions. The future of this work will be the inclusion of radiation in the equationing as well as experimental tests.

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6. RESPONSIBILITY NOTICE

The authors Priscila Marques da Paz and Juliana de Oliveira are the only responsible for the printed material included in this paper.