Condition Monitoring and Diagnosis of Steam Traps with Wireless Smart Sensors

Joana R. C. Faria[1], Sónia M. V. Semedo[1,2], Francisco J. A. Cardoso[1,2] , José Oliveira[1,2]
[1] Departamento de Física, University of Coimbra – 3004-516 Coimbra, Portugal
[2] Eneida – Wireless & Sensors, SA, 3030-199 Coimbra, Portugal
E-mail: joanafaria3@gmail.com, ssemedo@eneida.pt, fcardoso@ci.uc.pt, joliveira@eneida.pt

***Abstract*— An autonomous, wireless and self-powered smart sensor is described, addressing the condition monitoring and diagnosis of steam traps, whose performance degradation impairs energy efficiency in most of the process industries. The diagnostic criteria in the two possible failure modes of steam traps are presented, as well as the structure and technologies of the embedded devices for sensing, communication, and power supply, special attention being paid to the capability to run the system on the thermoelectric energy gathered from local pipes. Also, a platform supporting the integration of 'field' devices in large numbers is presented, which may address the data requirements in the scope of Asset Management.**

Keywords- Smart sensor; wireless network; energy harvesting; steam trap condition.

I. Introduction

Steam traps are vital elements in steam lines, as performance degradation of those strongly impairs energy efficiency in most of the process industries. In fact, one of the main concerns of today's automated world is energy waste and its consequences on overall productivity. Indeed, installing steam traps in large numbers throughout chemical and petrochemical plants serves that purpose; nevertheless, as one could expect, these devices aren't faultless – especially those built of mechanical parts only –, which easily allows a business case to be built addressing the on-line condition monitoring and the automatic status diagnosis of such devices.

A number of previous publications have dealt with this problem, and significant, representative approaches can be found in [1], [2] and [3], where the relevance of implementing permanent management mechanisms for steam traps are evaluated and discussed. Nevertheless, such solutions are only partial, as they don't encompass the different modes of failure in a typical steam trap, as described below.

Hence, the goal here consists in the ability to devise a criterion which could be embedded in a wireless smart sensor suitable to diagnose and report, in real time, malfunctioning traps. Smart sensors, in addition to having 'intelligence' to support complex applications, as the name suggests, are competent to self-calibrate and self-diagnose. Also, given the stringent restrictions implied by the ATEX-classified environments where steam traps are so often located, sensors were designed to be fully wireless, i.e., with no I/O ports of any kind, whether to support communication or for power supply.

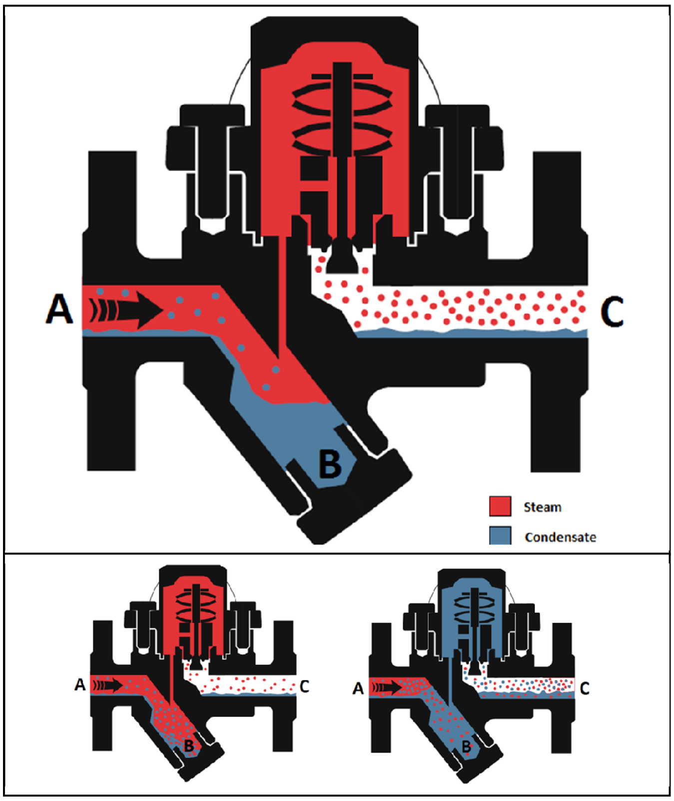

Figure 1. Steam traps – regular operation, leakage and blockage.

Therefore, besides using RF-based communication mechanisms, the system presented here resorts to energy-harvesting to power the different pieces of equipment, thus dispensing with batteries and the respective regular maintenance works. In this manner, besides safety in the presence of inflammable and/or explosive materials, smart devices are made fully autonomous, so that they can be dealt with as 'abandoned' appliances, from the maintenance point of view.

II. Steam Traps: Operation

Steam traps are automatic valves that allow condensate and non-condensable gases to be purged from steam lines, ideally with no steam loss. In general, steam traps operate in a purely mechanical manner, i.e., they do not require electronic modules. They operate by alternating between two opposite states: (i) open, thus allowing the drainage of condensate and non-condensable gases, and (ii) closed, where they block the steam flow. Thus, whenever a minimum amount of condensate is reached in a valve, this is automatically closed so that steam is prevented to leak; after some time, condensate and non-condensable gases build up and, therefore, force the mechanical switch into the open state. After the discharge of condensate, the system returns to the former state, thus completing the working cycle.

There are several types of steam trap designs [4]; just to support the common essentials on both working principle and modes of failure, a schematic depiction is presented in Fig. 1. Here, the top depiction illustrates regular operation, where the steam flow goes from pipe (A) to (C), while (B) represents the automatic valve. The basic principle of action in the automatic valve equals a flip-flop switching between two states: open and closed. When the valve is closed, pipe (B) is filled with condensate until it reaches a certain level and is ready for a safe discharge, i.e., with no loss of live steam. At this stage, the valve automatically opens and the condensate is released until the condensate level is minimum, this corresponding to a threshold level which avoids steam leaks. At this point the valve closes, thus completing the normal cycle of operation.

Steam traps, like all pieces of mechanical equipment, do fail repeatedly. According to Risko, J. "Average-quality traps may have just a 4-year life expectancy (which implies a 25% failure rate), while higher-quality steam traps may have an 8-year life expectancy (12.5% average failure rate)" [3]. In general, they fail in the open or in the closed position, causing a leakage or a blockage, respectively; in other words, a leakage occurs whenever steam traps fail in the open position and, therefore, allow the steam to flow incorrectly, causing energy loss in the system.

Table 1. Tipical temperature values measured at a field trip

Situation	T_A (ºC)	T_B (ºC)
Typical	**110 - 120**	**70 - 80**
Leakage	**100 - 110**	**90-100**
Blockage	**90 - 100**	**60-70**

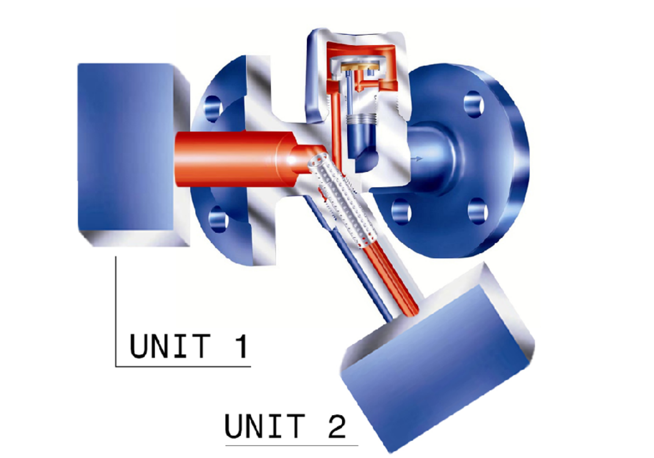

Figure 2. Schematic sensor implementation next to a steam trap

On the other hand, blockage occurs whenever there is a failure in the closed position: the condensate is not discharged and builds up along the pipe, thus causing its temperature to drop and, eventually, significant energy losses.

These two modes of failure can be correctly diagnosed through temperature measurement of hoses (A) and (B) in Figure 1, stated as T_A and T_B hereafter. Thus, in case of leakage, T_A drops and T_B increases, due to high-temperature steam. In case of blockage, both temperatures decrease. Typical temperature values for either abnormal circumstance are shown in Table 1.

III. System Architecture

According to the criteria described above, this solution diagnoses the operational condition of a steam trap based on temperature variations measured at both the respective inlet and outlet pipes, on either side of the trap body, as shown in Figure 2: therefore, the solution for a single trap comprises two detached units.

In order to make this solution suitable for hazardous areas, it is best to avoid any sort of cabling and, therefore, these units had to stay physically disconnected [5]. Communication between each pair of units comprising a smart sensor is based on Near Field Communication (NFC) technology [6], so that it does not contend with the other wireless networks used for large-scale system integration, as explained below, and given the fact that those units are separated by roughly ten centimeters, only.

The unit associated with the highest temperature pipe is the main unit and is the one in charge of external communications; the secondary unit sends temperature values to the main unit in the event of a temperature variation. As stated before, a smart sensor must be able to self-diagnose, thus the secondary unit must alert the main unit in case of malfunction detection. Furthermore, it also sends messages on a regular basis as 'proof of life'.

Each one of these two units integrates three modular parts which, functionally, correspond to: Sensing, Communication

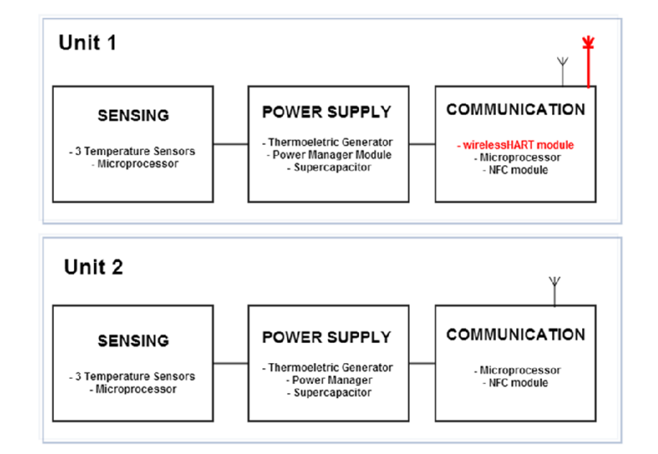

Figure 3. Block diagram of the two-part smart sensor

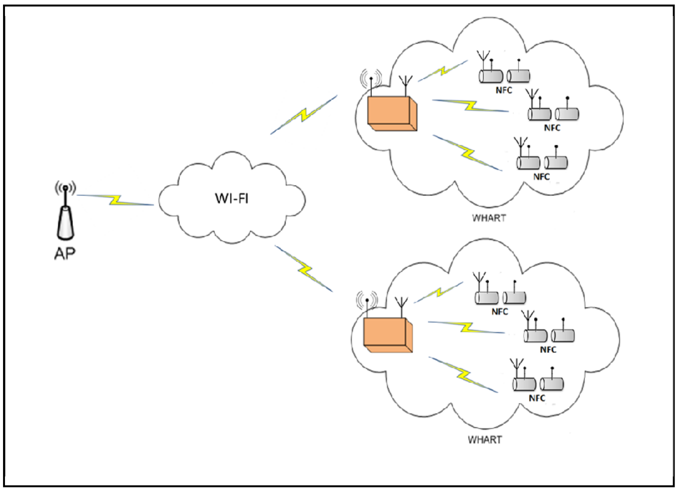

Figure 4. Communication System Architecture.

and Power Supply. Even though the communication modules are slightly different because only one communicates with other smart sensors located on other steam traps, their sensing and power supply modules are identical. Figure 3 depicts a block diagram of each module and unit.

As referred to above, both units in a smart sensor use NFC to communicate between them. A wider scale integration of a number of smart sensors is achieved through a low-power, low-range ISM (Industrial, Medical, and Scientific) wireless network operating in the 2.4 GHz frequency band – so as to avoid regulatory restrictions in the different ISM-radio regions –, wirelessHART [7] having been chosen given the fact that it is commonly accepted in both the Oil&Gas and the heavy chemical sectors.

Also, in order to cover large plant areas, it is advisable to resort to yet another mechanism of wireless communication: Wi-Fi, so that long distances can be dealt with, and no bandwidth troubles can occur whenever sensors of any sort, in large numbers, have to send messages to a central database/dispatch station. Figure 4 depicts a typical deployment of sensors made according to the above paradigm of system architecture; in this manner, efficiency in both communication and power consumption could be achieved.

IV. TECHNOLOGY

The practical implemention of the three modular blocks existing in each part of a smart sensor is addressed in both hardware and software technologies, as follows.

A. *Sensing*

This part is in charge of acquiring and processing temperature values. It comprises three temperature sensors organized as a triple modular redundancy structure, offering a self-diagnostic ability: in case one of these sensors measures differently from the other two by 5 ºC, at least, its result is ignored; persisting such a deviation, a permanent malfunction is determined and an alarm is issued, though the appliance as a whole still works well (while readings from the other two sensors concur). Temperature sensors are all ADT7301 from Analog Devices [8]

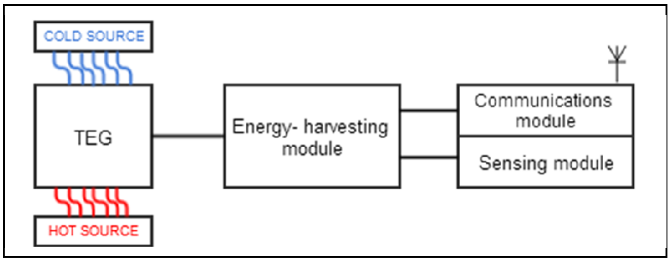

Figure 5. Schematic representation of the test setup

due to the adequate characteristics of both precision and repeatability [5], and the easy interfacing to the local host microcontroller – MSP430F2418, from Texas Instruments – via SPI serial bus.

B. *Communication*

A mechanism of Near Field Communication (NFC) supports peer-to-peer local communication between both parts in each smart sensor, this being based on TRF7970 technology, from Texas Instruments.

Wider integration of smart sensors over wirelessHART is carried out at unit 1 of a smart sensor, as depicted in Figure 3, through a dedicated mote – LTP 5900, from Linear Technology. In general, wirelessHART technology brought about important significant improvements in both security and reliability, as required by the automation industry. Thus, by resorting to synchonised mechanisms of frequency agility [8], real-time response for large mesh networks could be achieved. In this particular case, given the ‘intelligence’ of these sensors, they will only transmit alarms and warning messages, rather than data strings, so that communication over wirelessHART can be expected to be sparse and asynchronous, thus not being affected by the relatively low throughput of the underlying IEEE 802.15.4 technology. Nevertheless, as wirelessHART spreads throughout industrial plants and becomes common in closed loop industrial controls, sensor integration in the present case can only be seen as one more application relying on a single infra-structural network, where special attention has to be paid to such criterion as message priority, given the fact that data monitoring messages have lesser degree of priority than actuation control ones.

C. *Power Supply*

By using energy harvesting, the sensor is self-contained, with neither cabling for power supply (unadvisable in hazardous areas) nor batteries (which require regular maintenance). Each unit obtains energy from the thermal difference between the steam conduit (hot plate) and the air inside (cold plate), through a thermoelectric generator, and then stored in a 0.22 F supercapacitor that can be charged up to 5.2 V. Thus, a circuit integrating the thermoelectric generator connected to an ultralow voltage step-up converter and power manager – LTC 3109, from Linear Technology –, which charges the supercapacitor, was used in order to demonstrate the feasibility of the complete system: this circuit was coupled to a board with

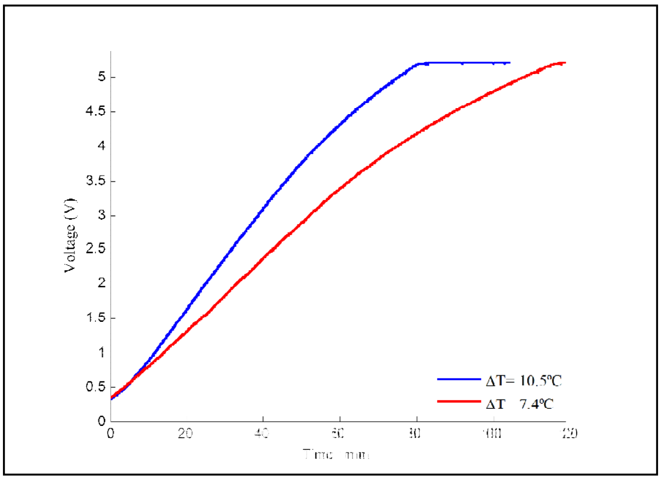

Figure 6. Supercapacitor charging for different temperature differentials.

a host microcontroller, a communication module and a temperature sensor as depicted in Figure 5.

Indeed, the real challenge in designing this solution consisted in the application of a thermoelectric energy harvesting module able to continuously sustain the operation of the entire equipment: (i) would it produce the necessary amount of energy?, (ii) how long would it take to charge the supercapacitor?, (iii) how many communication messages would be feasible with a fully charged capacitor, in case of no thermal source, i.e., what might be expected in terms of its autonomy?, and (iv) is the thermal differential between the steam conduits and the unit itself enough to produce the ammount of energy required?

Actually, although a number of thermoelectric energy harvesting solutions for wireless sensor nodes have been proposed and reported in the literature [9]-[19], they are naturally dependent on both the application and the deployment location, especially when it comes to fulfill the energy requirements in the absence of a thermal source. So, in order to obtain answers to the questions above, a number of tests were carried out, whose results and conclusions are presented next.

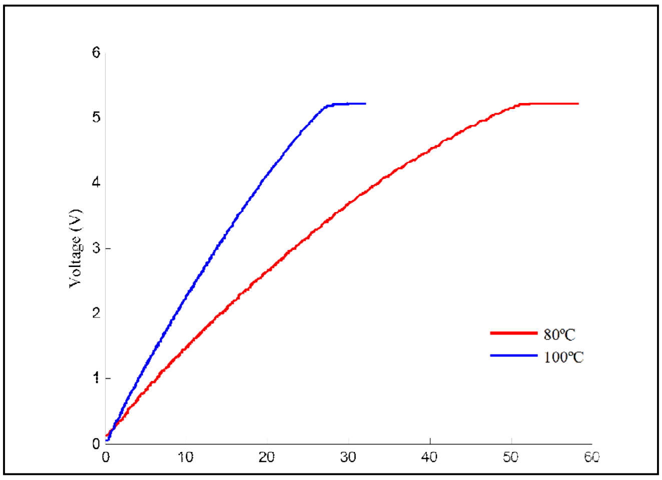

Figure 7. Supercapacitor charging for two temperature differentials.

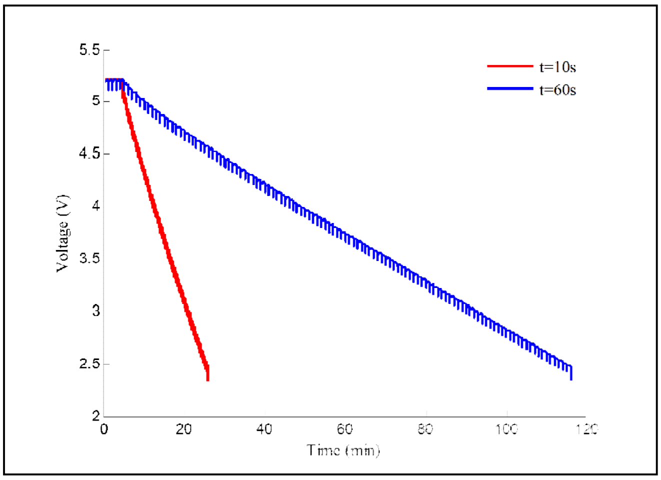

Figure 8. Supercapacitor discharging with no source of energy, for different communication periods.

V. Power Supply: Performance Evaluation

A simple setup, as described above and illustrated in Figure 5, led to charging rates as shown in Figure 6. Here, a 0.22 F supercapacitor was fully charged to 5.2 V, and, as expected, the charging process is faster at higher temperature differences: even with temperature differences of less than 10ºC, charging occurs in less than two hours' time. This is a very decent result as larger temperature differences will be dealt with in this application case, considering the high pipe temperatures around steam traps – in this test the hot source was roughly kept at 50 ºC.

Another test consisted in monitoring the charging evolution at higher temperatures in the hot side, especially in the range of 80-100 ºC, which are temperatures similar to the expected in steam traps. According to the results presented in Figure 7, charging times will be of less than one hour, in both units comprising a steam trap.

Regarding the energy consumed by both communication and sensing modules under normal operation, different tests were carried out: (i) firstly, evaluating discharging regimes of

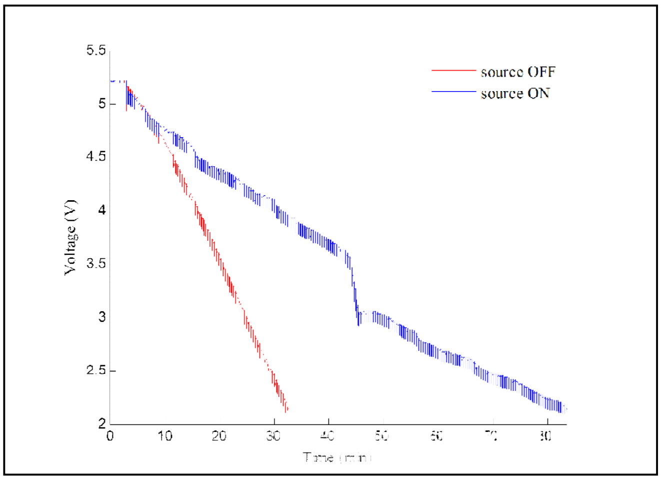

Figure 9. Evolution of supercapacitor voltage, with the thermoelectric module: (blue) connected, and (red) disconnected.

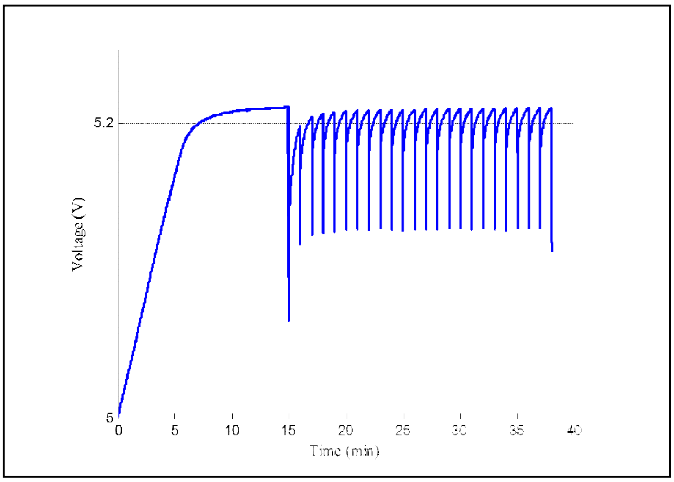

Figure 10. Supercapacitor voltage when communicating every minute.

the supercapacitor at different communication frequencies, with the thermopile disconnected, whose results are shown in Figure 8: the system is working for more than twenty minutes when communicating every ten seconds, thus transmitting one hundred and twenty seven messages successfully, which is a considerable result, and, as expected, when transmitting every sixty seconds, the discharging time increases by almost a factor of six, thus allowing one hundred and eighteen messages to be transmitted effectively – the system will be always capable of sending a warning message –, and (ii) then, evaluating the discharging regime, with and without the thermopile connected: results shown in Figure 9 correspond to a programmed condition where the system was transmitting every ten seconds, in either case of connected or disconnected thermopile, and, as one could predict, the discharging time rises significantly (twofold) in case the thermoelectric module is connected.

However, results show that the power supply module cannot guarantee continuous supply energy in case a communication rate of one message every 10s should be adopted. For this reason, other tests were carried out in order to determine a figure for the communication rate which allows continuous operation of the devices: at a communication rate of one message per minute, the system is fully capable of recharging the supercapacitor in between consecutive communications, as shown in Figure 10. This means that this system could be energetically autonomous.

VI. Conclusion

The system described here is a good example of the now emerging industrial instrumentation systems that integrate small, smart, and deeply embedded 'field' devices in large numbers, whose interoperability must be ensured with nested communication mechanisms, over disparate networks. In addition to wireless communication and functional autonomy, smart sensors here were made self-powered by converting thermal to electric energy, through thermopiles, thus exploiting the very physical variables that are continuously monitored for the purpose of diagnostic evaluation.

Acknowledgements

The autors thank Gestra – Flowserve Corporation for the permission to use the steam trap images previously shown. The work presented in this paper is partially financed by the Portuguese Foundation for Science and Technology, FCT; eneida® wireless & sensors, and QREN Portugal funds for IDT project Nr. 38650/2013.

VII. References

[1] A. Bahadori, "A simple predictive tool for monitoring steam loss in traps," *Chemical Engineering Research and Design,* vol. 90, no. 11, pp. 1896-1900, 2012.

[2] Emerson Process Management, "Impact of failed steam traps on process plants," April 2013. [Online]. Available: http://www2.emersonprocess.com/. [Accessed 2014].

[3] J. Risko, "Understanding Steam Traps," *Chemical Engineering Progress,* vol. 107, no. 2, pp. 21-26, 2011.

[4] Pentair Valves & Controls, "Yarway Industral Steam Trapping Handbook," February 2013. [Online]. Available: http://valves.pentair.com/valves/Images/YAWMC-0771-US_tcm106-37019.pdf. [Accessed 29 April 2014].

[5] F. Cardoso, S. Faria and J. Oliveira, "A smart sensor for the condition monitoring of industrial rotating machinery," in *Sensors, Proceedings of IEEE International Conference on* , Taipei, Taiwan, 2012.

[6] NFC Forum, "Near field communication," [Online]. Available: http://nfc-forum.org/. [Accessed 2014].

[7] HCF, "WirelessHART Technology," [Online]. Available: http://www.hartcomm.org/protocol/wihart/wireless_technology.html. [Accessed 2013].

[8] Analog devices, "Temperature sensors," 2011. [Online]. Available: http://www.analog.com/static/imported-files/data_sheets/ADT7301.pdf. [Accessed 5 May 2014].

[9] J. Eakburanawat and I. Noonyaroonate, "Development of a thermoelectric battery-charger with microcontroller-based maximum power point tracking technique," *Applied Energy,* vol. 83, no. 7, pp. 687-704, 2005.

[10] M. Kocoloski, C. Eger, R. Mccarty, K. Hallinan and K. Kissock, "Industrial Solid-State Energy Harvesting: Mechanisms and Examples," *ACEEE summer study on Energy Efficiency in Industry,* pp. 55-68, 2007.

[11] H. A. Sodano, G. E. Simmers, R. Dereux and D. J. Inman, "Recharging batteries using energy harvested from thermal gradients," *Journal of Intelligent material systems and structures,* vol. 18, pp. 3-10, 2006.

[12] A. Puşcaş, M. Carp, C. Kertesz, P. Borza and G. Coquery, "Thermal and voltage testing and characterization of supercapacitors and batteries," in *Optimization of Electrical and Electronic Equipment (OPTIM), 2010 12th International Conference on*, Brasov, Romania.

[13] X. Lu and S.-H. Yang, "Thermal Energy Harvesting for WSNs," *IEEE,* 2010.

[14] J. P. Carmo, L. M. Gonçalves and J. H. Correia, "Thermoelectric Microconverter for Energy Harvesting Systems," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,* vol. 57, no. 3, pp. 861-867, MARCH 2010.

[15] P.-H. Chen, K. Ishida, X. Zhang, Y. Okuma, Y. Ryu, M. Takamiya and T. Sakurai, "A 120-mV Input, Fully Integrated Dual-Mode Charge Pump in 65-nm CMOS for Thermoelectric Energy Harvester," *IEEE,* 2012.

[16] V. Leonov, "Thermoelectric Energy Harvesting of Human Body Heat for Wearable Sensors," *Sensors Journal, IEEE ,* vol. 13, no. 6, pp. 2284 - 2291, 2013.

[17] Y. Ramadass and A. Chandrakasan, "A Battery-Less Thermoelectric Energy Harvesting Interface Circuit With 35 mV Startup Voltage," *Solid-State Circuits, IEEE Journal of,* vol. 46, no. 1, pp. 333 - 341, 2011.

[18] R. Kappel, W. Pachler, M. Auer and W. Pribyl, "Using thermoelectric energy harvesting to power a self-sustaining temperature sensor in body area networks," in *Industrial Technology (ICIT), 2013 IEEE International Conference on*, Cape Town.

[19] C. Lu, S. P. Park, V. Raghunathan and K. Roy, "Analysis and design of ultra low power thermoelectric energy harvesting systems," in *Low-Power Electronics and Design (ISLPED), 2010 ACM/IEEE International Symposium on*, Austin, TX, USA, 2010.