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METHODOLOGY FOR REDUCING STEAM TRANSPORT COSTS WITH IR THERMOGRAPHY

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Abstract- Steam loss affects energy performance of thermal installations and increases energy bills. Some loss comes in the form of manageable and remediable leaks, while others are difficult to detect and to control. As a part of quality control of thermal installation within a company specialized in agri-food industry, we carried out diagnosis using thermal camera of a steam circuit and we noticed that temperature at the level of insulated pipes is reasonable (around 40 °C), while loss and leaks are visible on other parts of the circuit that are not isolated or poorly insulated. We assessed the impact of loss and leakage on steam production and consumption while highlighting the insulation role and found that annual operational cost savings resulting from insulation is around 164528 DH/year. Assessment of technical and economic potential of insulation in our study is based on calculations of:
• Heat loss and annual costs due to additional steam
• Total cost and economic thickness of insulation
• Total energy savings
• Annual operating cost savings
• Savings achieved by sealing leaks

Keywords: IR Diagnosis, Heat Loss, Steam Leakage.

1. INTRODUCTION

Steam boiler is mostly used in industries to produce steam, which is transported through steam pipes to meet the needs of companies for steam used for manufacturing and production processes. The amount of steam produced is not fully received at the end of the steam circuit due to steam loss and leakage. The impact is not only limited to economic side, but it also threatens the boiler system efficiency and longevity, as well as security and safety of people and goods.

The objective of this study is to model the steam circuit from boiler room to the process, by highlighting heat losses by convection and radiation as well as steam leaks using NDT instruments to measure and monitor energy parameters (temperature) in real time so as to establish the heat balance. We will assess also economic gains achieved by installing a proper insultation and by sealing the leaks. The socio-economic benefits of this study are the optimization of energy consumption and the improvement of the competitiveness of industrial companies.

2. LOSS AND LEAKS IMPACT ON STEAM PRODUCTION AND CONSUMPTION

In industrial processes, steam (saturated or superheated) is widely used for its advantages and physicochemical properties compared to other heat transfer fluids. According to ADEME (Environment and Energy Management Agency), it represents an important part in industry, particularly food and beverage industry which produce steam for several processes (drying, sterilization, cooking, etc.) [1, 2, 3, 4].

In industry, steam is not fully used due to unavoidable loss (radiation and convection loss) as well as leaks occurring on steam pipes. In our case, loss of steam is around 8%, which corresponds to 13% of the company's energy bill. As the impact is considerable, the consequences are not only limited to economic loss, but other risks arise. Some effective and practical actions allowing loss optimization and system performance improvement includes insulation of steam pipes and leaks sealing.

3. NDT TECHNICS IN MAINTENANCE AND QUALITY CONTROL

In a context marked by competition and in the objective of productivity improvement, quality control has become the best tool allowing companies to manage and optimize non-quality factors [5, 6]. Quality control promotes smooth flow of maintenance operations while avoiding unforeseeable interruptions impacting pro-duction and increasing operating costs.

Among the rapid and effective diagnostic technics, we find the non-destructive testing of materials (NDT) based on measurement and diagnostic tools allowing integrated and continuous quality control from production to distribution. The most used NDT technics are ultrasound, X-ray Radiography, Eddy currents, and IR Thermography [6].

In preventive and predictive maintenance, infrared thermography (IR) is considered as the most efficient and cost-effective tool allowing anticipation of failures and quick actions during maintenance operations [7-9].

4. ECONOMIC THICKNESS OF INSULATION

Piping systems are used to distribute steam, return condensate, and remove air and non-condensable gases [10]. Not only the amount of heat loss along steam pipes is considerable, especially due to steam leakage and lack of insulation, but also heat loss is important on other boiler parts like valves which lose an amount of heat equivalent to heat lost by 1.7 m uninsulated pipe [11].

The aim of insulation is to trap heat in order to prevent heat flow from escaping to the outside. It not only makes steam pipes more reliable, but it also optimizes heat loss and maintains good steam quality while reducing condensation. For safety reasons, insulation must cover all steam system components (pipes, valves... etc.) and any surface with a temperature above 55 °C [12]. Insulation material for steam pipes should have at least a low thermal conductivity and an optimal and resilient density.

A minimum thickness of insulation is required to ensure steam safety and quality. Figure 1 shows economic thickness versus costs per year, which represent the minimum cost on curve *C* [13, 14]. The curve *C* is the total cost, which includes curve A for insulation costs and *B* for heat loss costs obtained from calculations of invested capital, money interest, depreciation, maintenance, energy price, heat loss rate, hours of operation.

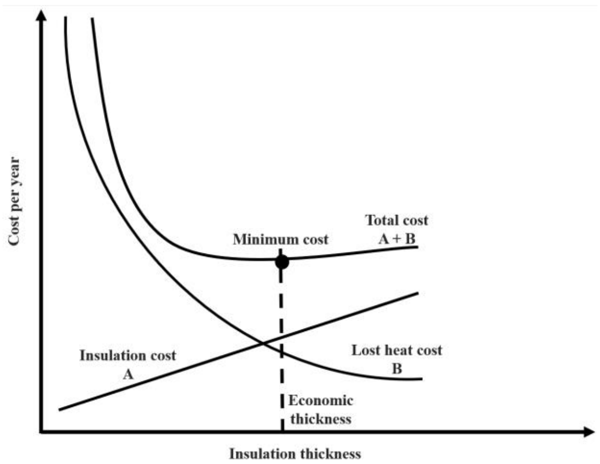


Figure 1. Economic thickness of insulation [13, 14]

4.1. Heat Loss and Annual Costs

Heat loss and annual costs due to additional steam are calculated as below for uninsulated and insulated pipe. The exchange surface is estimated to "*S*=65 m²" and steam temperature is "T_i=156 °C". Heat loss in watt includes convection loss Equation (1) and radiation loss Equation (2):

$$Q_{conv} = h \times S \times \Delta T \tag{1}$$

$$Q_{rad} = \sigma \times \varepsilon \times S\,(T_i^4 - T_a^{\,4}) \tag{2}$$

Annual costs due to additional steam are obtained from Equation (3) [12], and numerical data for loss and annual cost calculations are presented in Table 1.

$$A_c = \frac{Q \times t \times P}{h} \tag{3}$$

We noticed that uninsulated pipe heat loss is 203.6 kW while insulated pipe lose only 88.1 kW. Considering a steam cost of "*P* ≈298 DH/ton", annual costs due to additional steam for insulated pipe are 69210.6 DH/year against 97154.1 DH/year for uninsulated pipe.

Table 1. Heat loss and annual costs

Quantity	Symbol	Value	Unit
Ambient temperature	T_a	20	°C
Heat transfer coefficient (uninsulated)	h_s	14	W/m²K
Heat transfer coefficient (insulated pipe)	h_i	1	W/m²K
Stefan's constant	σ	5.67×10^{-8}	W/m².K^4
Surface emissivity	ε	0.8	-
Annual operating hours	t	5800	h/year
Enthalpy of vaporization of water	h	2200	kJ/kg

4.2. Heat Loss and Energy Savings

For a pipe (DIN 100 mm) transporting steam over a distance of 200 meter, we calculate total energy savings achieved with and without insulation having a thickness of 50 mm as presented in Table 2. Only heat loss by convection were calculated using heat transfer coefficient U which is obtained from Equation (4) [15].

$$\frac{1}{U} = \frac{d_{is}}{d_i \times h_i} + \frac{d_{is} \times \text{In}(\frac{d_0}{d_i})}{2k_p} + \frac{d_{is} \times \text{In}(\frac{d_{is}}{d_0})}{2k_{is}} + \frac{1}{h_0} \tag{4}$$

where, *d* is insulation diameter mm, *k* is thermal conductivity W/m.K, *i* is inner, *o* is outer, *is* denotes insulation and *p* denotes pipe.

Total energy saved is equal to energy saved without insulation minus energy saved with insulation. While energy cost saved is equal to energy cost without insulation minus energy cost with insulation. The boiler operates for 8000 hours/year with an estimated efficiency of 85% and burns fuel, which costs 7930 DH/ton. Measured surface temperature is 180 °C and ambient temperature is 25 °C.

Table 2 shows that in the absence of insulation, heat loss (around 141 W/m².K) contribute to increase energy consumed during steam production period. Insulation reduces loss to 11 W/m².K thus contributing to energy savings of 1226294 kWh and economic gain of 836022 DH during annual operating period of the diagnosed steam pipe.

Table 2. Total energy savings

Calculation	Unit	Insulated	Uninsulated
Heat transfer coefficient (*U*)	W/m².K	14	1
Surface (*S*)	m²	63	126
Heat loss *Q*	kW	141	11
Energy consumed	kWh	1128674	86324
Fuel	ton/Ans	114	9
Energy cost	DH	905254	69232
Energy saved	kWh	1226294	
Energy cost saved	DH	836022	

4.3. Total Cost and Economic Thickness of Insulation

Economic thickness of insulation is the minimum value of total cost as shown in Equation (5):

$$C_{tot} = C_{loss} + C_{inst} \tag{5}$$

where, Heat loss cost (C_{loss}) is the product of heat loss (W/m) and cost factor (DH/W), values of heat loss per meter (Q_{loss}) are obtained from Figure 2 for a pipe of 50mm section transporting steam at 100 °C [12]:

$$C_{loss} = Q_{loss} + C_f \tag{6}$$

Table 3 includes cost of installed insulation (C_{inst}) for different thicknesses of insulation and the value of cost factor (C_f) calculated with Equation (7) is around 16.4 DH/W [12, 16]:

$$C_f = \frac{f}{\eta} + 3600 \times h \times P \times 10^{-9} \tag{7}$$

where, C_f is fuel price per higher calorific value as 0.75 DH/kWh, η is boiler efficiency as 80%, h operation period as 4000 h/y and P is evaluation period as 5 years.

For 19 mm thickness, insulation cost is 29.6 DH/m while heat loss is around 37 W/m as shown in [17]. Heat loss during evaluation period cost’s 606.8 DH/m, so total cost’s 636.4 DH/m. By repeating calculation for different thicknesses of Table 3, we obtain economic thickness (38 mm) corresponding to minimum value of C_{tot} (440 DH/m).

Table 3. Economic thickness optimal value

Insulation thickness	Heat loss (Q_{loss})	Cost factor (CF)	Heat loss cost (C_{loss})	insulation cost (C_{ins})	Total cost (C_{tot})
Mm	W/m	DH/W	DH/m	DH/m	DH/m
19	37	16.4	607	29.6	635.8
25	30	16.4	492	42.3	533.7
32	26	16.4	426	49.7	475.5
38	23	16.4	377	62.3	440
50	20	16.4	327	174.3	501.8

4.4. Annual Operational Cost Savings

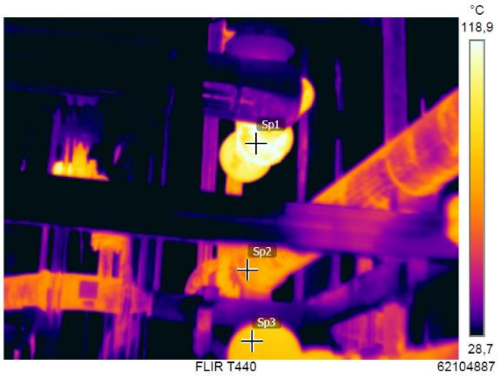
We calculated annual operational cost savings by glass wool insulation efficient at 92% with a thermal conductivity of 0.04 W/m.K. The methodology as described in literature [18] is based on calculation of total annual heat loss through steam pipes. During our diagnosis, we identified the below steam pipes as shown in Figure 2:

- 264 m of 2.54 cm diameter pipe at 150 psig
- 61 m of 5.08 cm diameter pipe at 150 psig
- 47 m of 10.16 cm diameter pipe at 15 psig

Heat loss for different diameters of steam pipes is obtained from Table 4 for 30.48 m of uninsulated steam pipe, and considering steam price of 0.15 DH/kWh, annual operational cost savings are estimated at 164528 DH/year as shown in Table 5.

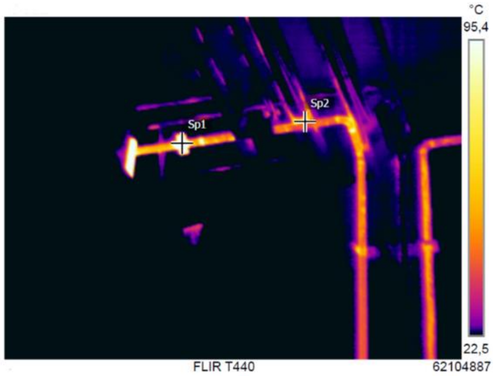
5. HEAT LEAKS FROM STEAM PIPES

Since leaks are obvious and permanent sources of steam and heat loss, their impact is considerable on production and distribution costs, on employee safety and environment, as well as on steam circuit longevity. We focused our diagnosis on leaks detected by IR camera, in order to quantify steam loss and to assess energy savings potential resulting from sealing operations.



Measures	°C
Sp1	120.3
Sp2	78.9
Sp3	90.5

Parameters	
Emissivity	0.93
Refl. Time	20 °C
Geolocation	
Compass	50 ° NE



Measures	°C
Sp1	113.1
Sp2	79

Parameters	
Emissivity	0.93
Refl. Time	20 °C
Geolocation	
Compass	211 ° NE

2. Diagnosed steam circuit

Table 4. Heat loss per 30.48 m of uninsulated steam pipe (kWh/year)

Steam pipe diameter (cm)	Steam pressure (psig)			
	15	150	300	600
2.54	41020	83505	109875	145035
5.08	68855	140640	184590	246120
10.16	121595	249050	328160	439500
20.32	216820	451220	594790	798425
30.48	309115	644600	852630	1148560

Table 5. Total heat loss in kWh/Year

Pipe diameter (cm)	Pipe length (m)	Heat loss for 30.48 m of non-insulated pipe in kWh / Year	Total heat loss in kWh/Year
2.54	264	83505	723271.6
5.08	61	140640	281464.5
10.16	47	121595	187498.8
Total heat loss in kWh/Year			1192235

For six identified leaks having different diameters as shown in Table 6, we calculated steam flow rate lost at different pressure basing on the table of steam loss through orifices [16]. Total steam loss through leaks is estimated at 677.4 ton/year during an operating period of 5800 hours. Annual loss cost due to leaks is around 277750 DH where steam cost 410 DH/ton.

These leaks can be eliminated by sealing, which consists on forming a seal around the leak by positioning a collar or a box on it and by injecting a sealing compound under pressure [19, 20]. Sealing operations are carried during steam production and on circuits transporting pressurized steam. They not only improve safety on production lines and protect the environment, but also strengthen quality control of heat production system.

Table 6. Steam flow rate per leakage diameter

Leak	Pressure		Diameter		Flow rate	
	bar	lb/po²	mm	po	lb/h	Kg/h
1	5	75	4.5	3/16	93	42.1
2	5	75	4	5/32	64.5	29.3
3	5	75	3	1/8	41.3	18.7
4	5	75	3	1/8	41.3	18.7
5	5	75	2	3/32	15.4	6.9
6	5	75	1	1/32	2.58	1.1
Total						116.8

6. CONCLUSION

We evaluated influence of loss and leaks on steam production and consumption. Then, we reviewed NDT technics role in maintenance and quality control, as well as the advantages of economic thickness of insulation and their effect on thermal installation performance. We carried out our diagnostic on steam circuit of a company specialized in agri-food industry, in order to assess technical and economic potential of insulation of steam circuit. We calculated heat loss and annual costs for the case of 140m long pipe and found that heat loss goes from 203.6 kW to 88.1 kW with insulation. Annual costs due to additional steam are estimated at 69210.6 DH/year for insulated pipe against 97154.1 DH/year for uninsulated pipe.

We calculated heat loss and energy savings for a 200mpipe and found that insulation allows reducing loss to 11 W/m². K and contribute achieving energy savings of 1226294 kWh and economic gains of 836022 DH during annual operational period. Basing on calculations of total cost and economic thickness of insulation, we obtained economic thickness of 38 mm which corresponds to minimum value of C_{tot} (440 DH/m). We also evaluated annual operational cost savings for a 372m long steam pipe and found that cost savings are estimated at 164528 DH/year. Finally, we quantified steam loss by leaks at 677.4 ton/year, and we evaluated energy saving potential resulting from sealing operations at 277750 DH.

Diagnostic with IR thermography contribute to improve system performance, and to save additional costs related to maintenance operations by identifying the root of energy loss on steam pipes. Boilers and steam pipes should be verified more often with NDT tools in order to avoid non-conformities during regulatory control and verification of thermal installation. Boiler owners should provide tools such as IR camera to ensure a continuous control of steam production and distribution, and to avoid accident and to improve maintenance operations. Data could be collected then from IR images and used to analyze temperature evolution, to assess pipes insulation conditions, as well as to prevent eventual risks.

As the annual cost of heat loss and leakage is higher than the cost of implementation of a fixed IR camera, this NDT Techni should be included as a requirement by regulations during conformity assessment of steam boilers.

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BIOGRAPHIES

Anas Meksoub was born in Oujda, Morocco on November 05, 1988. He is an industrial engineer and graduated in 2011 with more than 10 years' experience in industrial field and working as technical advisor for a multinational company of TIC. He has expertise in energy efficiency in the industrial environment. His works concerns optimization of losses occurring on industrial boilers and energy efficiency in industrial field. He is following his doctoral studies at Mohammed Premier University, Oujda, Morocco about Energy optimization of industrial processes, which is focused on industrial maintenance and energy efficiency. He has two publications on steam boiler efficiency and performance improvement.

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