IRREVERSIBILITY ANALYSIS IN THE THERMODYNAMIC DESIGN OPTIMIZATION OF STEAM DISTRIBUTION PIPELINES

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Abstract. *The entropy generation minimization was considered for analysis as a thermodynamic optimization technique, in order to search for the optimal diameter that minimizes the avoidable irreversibilities associated to heat loss and pressure drop in the steam flow pipelines. In this work, special attention was given to the irreversibility analysis and to the thermodynamic optimization in designing the steam line connecting the boiler to consumers for electricity generation and process heating purposes. As design requirements, the mass flow rate demanded by the steam turbine, as well as the temperature and pressure necessary for the operation are considered known variables to the problem. The equivalent length of the pipeline is also considered as fixed parameter. An existing biomass cogeneration plant of about 4.7 MW was considered for analysis. The steam pipelines were designed taking into account the thermodynamic optimization technique as proposed here. The simulation performed considering an existing cogeneration plant of 4.7 MW at flow steam rate of 25 ton/h showed a strong influence of both the insulation and steam flow rate over the irreversibility rate. As expected, searching for the optimal diameter of insulated pipelines, it was demonstrated a strong influence of the pressure drop and a more weak influence of the heat loss irreversibilities.*

Keywords: *Steam pipelines, Entropy generation, Exergy*

1. Introduction

Combined heat and power systems and steam power plants are considered for analysis in this work. The thermal energy generated by steam power plants must be transferred to steam turbines or consumer systems by steam pipelines which have to be appropriately designed to minimize energy waste associated to heat loss and viscous dissipation, besides other technical and constructive factors. In the cases where the steam distribution network has a complex structure consisting of long pipelines, an adequate design becomes more important and methods for design optimization may be required. Since cogeneration or thermal power plants are systems intended to have a long life-cycle, the thermal design optimization may imply in significant energy conservation in a long-term perspective. It has been stated by many authors that any thermal design optimization must be in accordance with both the first law and the second law of thermodynamics (Bejan et al., 1996). Recently Poredos and Kitanovski (2002) suggested the exergy loss as a basis for determining the price of thermal energy in district heating systems. Distributed heating networks or steam pipelines usually supply different consumers at different temperatures or pressures. In most cases the price are fixed, depending only on the heat amount and not on the quality of the energy.

This paper investigates the application of the Entropy Generation Minimization (EGM) method (Bejan, 1996) in the design optimization of service pipes in distribution systems of cogeneration plants. The EGM method applied to the piping network design is a way of thermodynamic optimization by minimizing the irreversibilities associated with the heat transfer and viscous dissipation of the steam internal flow and the heat loss to the environment. By minimizing the entropy generation, the exergy at the consumer systems is maximized and the system is thermodynamically optimized. The irreversibilities associated with the viscous dissipation and the heat losses to the environment are calculated as a function of the pipeline diameters. This analysis provides the optimum internal diameter for minimization of entropy generation, which is the calculated diameter on the point where the best trade-off between heat transfer and viscous dissipation occurs. This method presents an additional alternative for the design of the piping dimensions since this type of analysis is not usually done in typical pipeline design although already treated in a theoretically point of view with the availability analysis approach (Moran, 1989).

The results and advantages of the method to this type of application are discussed. A biomass cogeneration plant of about 4.7 MW is analyzed. The steam pipelines connecting the central power plant to consumers are designed taking into account existing technical data, and the thermodynamic optimization described.

2. Steam Pipelines Design

Steam pipelines are usually designed following criteria associated to the steam velocity, pressure drops, vibration, operational and investment costs. Thermal expansion and stresses are also considered to assure flexibility and security of the piping system. The selection of the most appropriated type and size of insulation, control valves, steam traps and other components will enable the system to operate near the optimal manner, all bear directly on the efficiency and economy of the plant. Several computer-aided approaches for the design of pipelines exist. Nevertheless, there is no practical concern about the irreversibilities or steam exergy destruction along the pipeline. Following this idea, the best design should be associated to the minimum irreversibility rate possible, within the limits imposed by physical, technological, economic and other constraints (Kotas, 1995).

Special attention is given in this work to the irreversibility analysis and to the thermodynamic optimization in designing the steam line connecting the boiler to consumers for electricity generation and process heating purposes. The objective is to minimize the steam flow entropy generation, searching for the optimal diameter that minimizes the avoidable irreversibilities associated to heat loss and pressure drop.

As design requirements, the mass flow demanded by the steam turbine, as well as the temperature and pressure necessary for the operation are considered known variables to the problem. The equivalent length of the pipeline is also considered as a fixed parameter since this value depends on the layout and physical aspects of the cogeneration plant (configuration of the pipeline system, distance from the steam generator, auxiliary equipment, etc) rather than on thermodynamic design. For different diameters, the required pressure and temperature leaving the steam generator are found and, consequently, the fuel consumption in the power plant.

The heat loss to the environment can be calculated by the conventional heat transfer techniques, where the expression of the total heat loss per unit length is:

$$q' = \frac{T_F - T_E}{R_T} \tag{1}$$

T_F is the temperature of the flow, T_E is the average environment temperature, and R_T is the total thermal resistance per unit length of the specific constructive design of the pipeline system, considering all the possible ways of heat transfer to the environment. The total thermal resistance mainly depends, besides the properties of the fluids and the materials involved, on the diameter of the pipeline. Since the decision variable of this problem is the internal diameter, all the other dimensions, such as external diameter, insulation thickness, burial depth, and so on, are defined as a function of the internal diameter. By this way, the total thermal resistance can be calculated primarily as a function of the internal diameter when regarding the aspects involved with the construction of the pipeline system.

The pressure drop can be evaluated for the equivalent length of the pipeline, L, by the generic equation:

$$\Delta p = f \frac{4L}{D} \frac{\rho V^2}{2} + \left(\frac{4\dot{m}}{\pi D^2} \right)^2 \left(\frac{1}{\rho_2} - \frac{1}{\rho_1} \right) \tag{2}$$

where V is the corresponding average velocity:

$$V = \frac{\dot{m}}{A\rho} \tag{3}$$

The second term of the Equation 2 is applied when there is significant density variation between the inlet and the outlet of the pipeline. If that situation is not considered, then only the first term is applied considering an averaged density between the inlet and the outlet, where

$$\rho = \frac{1}{2}(\rho_1 + \rho_2) \tag{4}$$

For a given internal diameter, once defined the state of the steam at the end of the pipeline, a next step is to find the required pressure and temperature leaving the steam generator, solving iteratively the problem of heat loss and pressure drop. The energy lost to the environment by means of heat transfer (Eq. (1)) must be reflected in the energy balance:

$$q'.L = \dot{m} \cdot (h_1 - h_2) \tag{5}$$

Equations 1, 2 and 5 provide the necessary equation system to obtain the required temperature and pressure at the pipeline inlet.

The computer program EES – Engineering Equation Sover (Klein and Alvarado, 2002) was used to simulate the problem, considering the feasible velocity range for superheated steam, usually between 30 m/s and 75 m/s (ASHRAE, 1996). The upper recommended velocity is associated to a reliable operation of the piping system. The feasible range of internal diameters possible for a proper operation is determined by the mass flow, $\dot{m}$, required by the steam turbine or consumer, according to the equation:

$$D = \sqrt{\frac{4\dot{m}}{V\pi\rho}} \tag{6}$$

3. Irreversibility Analysis

The Entropy Generation Minimization (EGM) applied to the design of the piping network design as a way of thermodynamic optimization by minimizing the irreversibilities associated with the heat transfer and viscous dissipation of the steam internal flow and the heat loss to the environment. The entropy generation rate is calculated considering the physical model showed in Fig (1), taking into account a control volume of a length *dx* and section *A* of the pipeline.

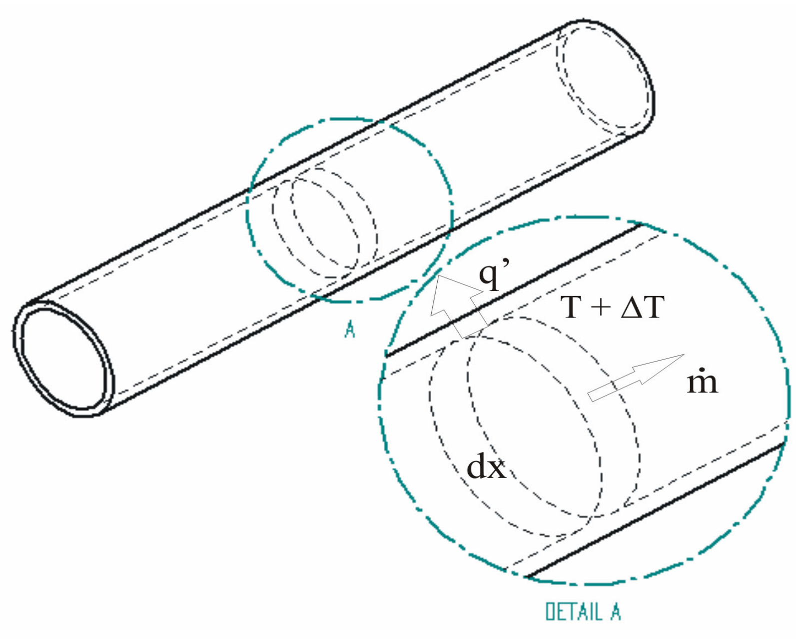

Figure 1. Physical model of the pipeline.

The equations relating the energy and entropy balances are:

$$\dot{m}\frac{dh}{dx} = q' \tag{7}$$

$$\dot{S}'_{gen} = \dot{m}\frac{ds}{dx} - \frac{q'}{T + \Delta T} \tag{8}$$

where q' and $\dot{S}'_{gen}$ are the heat loss and the entropy generation rate per unit length. As showed by Bejan, (1996), using the canonical relation and combining the equations of energy and entropy balances one finds the entropy generation rate:

$$\dot{S}'_{gen} = \frac{q'\Delta T}{T^2(1 + \Delta T / T)} + \frac{\dot{m}}{\rho T}\left(-\frac{dP}{dx}\right) \tag{9}$$

or

$$\dot{S}'_{gen} \cong \frac{q'\Delta T}{T^2} + \frac{\dot{m}}{\rho T}\left(-\frac{dP}{dx}\right) \tag{10}$$

where the first term of the right side concerns to the heat loss and the second term concerns to the viscous dissipation. Introducing the Nusselt number, *Nu*, the friction factor, *f*, and the internal diameter in Eq. (10), results:

$$\dot{S}'_{gen} = \frac{q'^2}{\pi k T^2 Nu} + \frac{32\dot{m}^3}{\pi^2\rho^2 T}\frac{f}{D^5} \tag{11}$$

Equation (11) shows that when small values are assigned to variable D, while in the first term the heat loss decreases, in the second term the pressure drop increases, thus increasing the entropy generation rate. And towards the direction of increasing the diameter D, while the heat loss may become of more importance, the pressure drop decreases. Therefore, Equation (11) shows that the best trade-off between heat loss and pressure drop must be found in order to minimize the entropy generation. The value of D which minimizes entropy generation is also the internal diameter size of the pipeline where the system is thermodynamically optimized. This value can be found by computing Equation 11 for a selected range of D and so identifying the point where the curve has a minimum.

The total irreversibility associated to the steam flow is calculated according to:

$$\dot{I} = T_0 \cdot \dot{S}_{gen} \tag{12}$$

and the intrinsic irreversibility corresponds to the minimum entropy generation associated to the optimal diameter. Alternatively the irreversibility can be found according to a exergy balance applied to the entire pipeline:

$$e_1 - e_2 = T_0 \cdot \dot{S}_{gen} \tag{13}$$

where, for i = 1 to 2,

$$e_i = h_i - h_0 - T_0 \cdot (s_i - s_0) \tag{14}$$

The temperature T_0, enthalpy h_0 and entropy s_0 are related to the dead state (25ºC; 101,3 kPa). Since the exergy decreases at the outlet of the pipelines in comparison with the exergy at the inlet, the expression $T_0 \cdot \dot{S}_{gen}$ is also called the exergy destruction, and is related to the entropy generation caused by heat loss and viscous dissipation.

4. Preliminary Results and discussion

Preliminary results are shown for a design case of a biomass cogeneration system. The cogeneration plant consists of a steam generator (25 ton/h) and a condensing/extracting steam turbine (4.7 MWel). Steam enters the turbine at 45 bar, 400ºC. An amount close to 25 ton/h is extracted from the turbine and distributed via a branched pipeline for process heating. The required pressure by the consumers is 10 bar abs. The distance between the turbine and the farthest consumer point is about 400 m.

An irreversibility analysis is now performed to two scenarios, as described in Fig. (1). Scenario 1 corresponds to the steam pipeline connecting the boiler to the turbine. Scenario 2 corresponds to a single pipeline connecting the extracting turbine to the steam consumer of the plant. The simulation was performed considering a flow steam rate of 25 ton/h and an internal diameter range from 80 to 800 mm. The thermal insulation was defined according commercial requirements as suggested by the manufacturer.

Table 1. Scenarios analyzed

Scenario	Pipeline		
	Length [m]	Required pressure [bar abs]	Required temperature [ºC]
1	100	45	400
2	400	10	(*)

*Depending on the steam turbine extraction condition

In Figure (2) are shown the heat loss and pressure drop concerning the steam pipeline for Scenario 1. As expected, it is clear from Figure 3 the strong influence of both the insulation and steam flow rate over the irreversibility rate. The minimum point represents the intrinsic irreversibility. One can see as the minimal point is shifted towards the right.

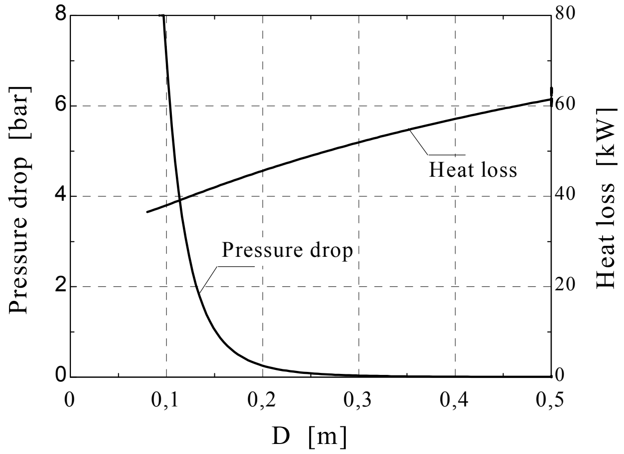

Figure 2. Trade-off between heat loss and pressure drop for 25 ton/h vs. internal diameter of the pipeline (Scenario 1).

For Scenario 1 and steam flow rate equal to 25 ton/h, the intrinsic irreversibility is shown in Fig. (4), for both uninsulated and insulated pipeline. For the uninsulated pipeline, the optimal internal diameter is somewhat about 150 mm. On the other side, for insulated pipeline the optimal diameter is 247 mm. The corresponding steam velocity and intrinsic irreversibility are 9.4 m/s and 29 watts, respectively. It is clear from Fig. (4)Figure that the abrupt decreasing of the irreversibility curve up to the minimum point and very smooth increasing for larger values. In this case, the irreversibility curve resembles the pressure drop curve, demonstrating the more weak influence of the heat loss. For designing purpose, it is important to observe the recommended velocities range for superheated steam (30 to 75 m/s) and the corresponding internal diameter of the pipeline (80 to 140 mm). So, from the thermodynamic point of view, for Scenario 1, the best design should consider a larger diameter. That is the point for a reflection, once conventional methods for designing steam pipelines do not consider exergy destruction. In a worst case, if an 80 mm internal diameter is selected, the irreversibility shall be somewhat like 310 W (see Fig. (4)Figure). Although, in case of the optimal diameter, it appears not so large, one should consider the corresponding exergy cost loss. In a rough analysis, the difference between the irreversibilities of both cases is just 281 W not converted into electricity, or 48 MWh, considering a whole 20 years life time of the plant.

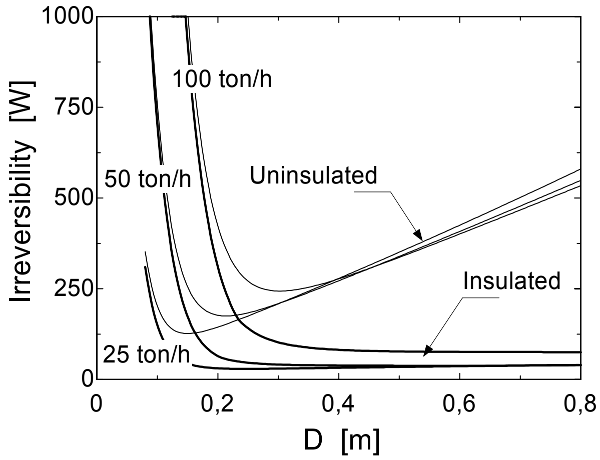

Figure 3. Irreversibility rate vs. internal diameter for different steam flow rates (Scenario 1)

In Figure (5) are shown the heat loss and pressure drop concerning the steam pipeline for Scenario 2. Saturated steam at 10 bar of absolute pressure is required for heating purposes only. However superheated steam is extracted from the turbine for delivering to the consumer actually. The corresponding irreversibility curves are shown in Fig. (6). For non insulated pipeline, the optimal internal diameter was estimated somewhat about 260 mm. For insolated pipeline the optimal diameter was found 487 mm and the corresponding steam velocity and intrinsic irreversibility are 7.5 m/s and 42 watts, respectively. Again, it is clear the abrupt decreasing of the curves up to the minimum point, showing the stronger influence of the pressure drop along the pipeline. The irreversibility curve resembles the pressure drop curve and the weak influence of the heat loss. For designing purpose, it is important to observe the recommended velocities range for superheated steam (30 to 75 m/s) and the corresponding internal diameter of the pipeline (120 to 240 mm). So, from the thermodynamic point of view, the best design is relatively far from the corresponding applied diameter. In this scenario, once again considering the corresponding the exergy cost loss, if an 120 mm internal diameter is selected, the difference between the irreversibilities of both cases is about 659 W, or 114 MWh, considering a whole 20 years life time of the plant.

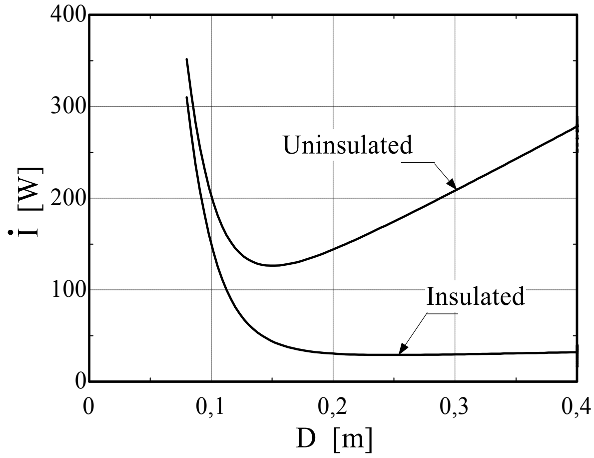

Figure 4. Irreversibility rate vs. internal diameter (uninsulated and insulated pipelines, Scenario 1: 45 bar; 400ºC; 100m; 25 ton/h)

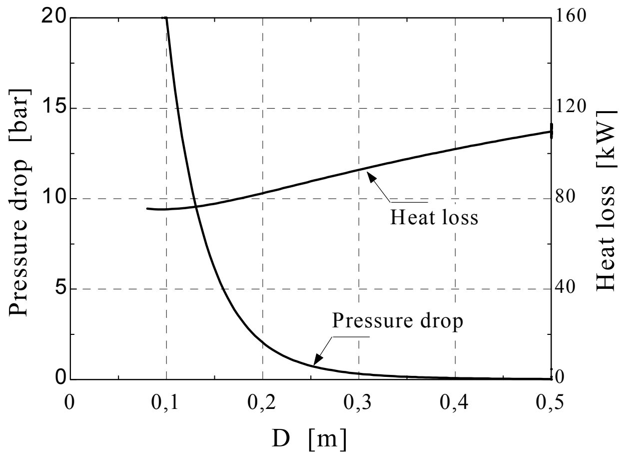

Figure 5. Trade-off between heat loss and pressure drop for 25 ton/h vs. internal diameter of the pipeline (Scenario 2).

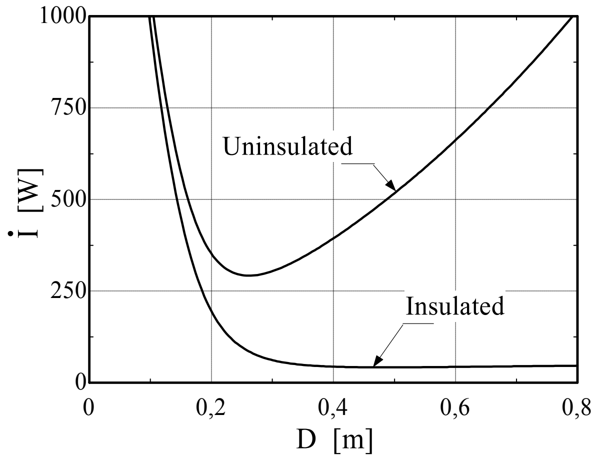

Figure 6. Irreversibility rate vs. internal diameter, for uninsulated and insulated pipeline (Scenario 2)

5. Conclusion

The entropy generation minimization was considered as a thermodynamic optimization technique, in order to search for the optimal internal diameter that minimize the avoidable irreversibilities associated to heat loss and pressure drop in a steam flow pipeline. The simulation performed considering an existing cogeneration plant of 4.7 MW at flow steam rate of 25 ton/h showed a strong influence of both the insulation and steam flow rate over the irreversibility rate. Searching for the optimal diameter of insulated pipelines, the irreversibility curve resembles the pressure drop curve, demonstrating weak influence of the heat loss.

Special attention could be given to the irreversibility analysis and to the thermodynamic optimization in designing the steam pipeline. Conventional methods do not consider exergy destruction. It is important to remind the recommended steam velocity range (ASHRAE, 1993) and the corresponding internal diameter of the pipeline. From the thermodynamic point of view, the best designs are relatively far from the corresponding applied diameters, but the results of irreversibility rates are not appreciably different. A global exergy cost loss in this work was found somewhat like 940 watts, no more than 162 MWh if considering a whole 20 years life time of the plant.

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