Strathprints Institutional Repository

Fernandez, J. and Blanco, E. and Parrondo, J. and Stickland, M.T. and Scanlon, T.J. (2001) *Ironwork of Teixois-Taramundi (Asturias) Spain.* In: International Symposium on History of Machines and Mechanisms, HMM 2000, 2000-05-11 - 2000-05-13, Cassino, Italy.

Fernandez, J. and Blanco, E. and Parrondo, J. and Stickland, M.T. and Scanlon, T.J. (2001) Ironwork of Teixois-Taramundi (Asturias) Spain. In: International Symposium on History of Machines and Mechanisms, HMM 2000, 11-13 May 2000, Cassino, Italy.

IRONWORK OF TEIXOIS-TARAMUNDI (ASTURIAS), SPAIN

J Fernández
Universidad de Extremadura, Dpto. de Electrónica e Ingeniería Electromecánica
Avda. de Elvas s/n. 06071 Badajoz, Spain
ffrancos@unex.es

E Blanco, J Parrondo
Universidad de Oviedo, Área de Mecánica de Fluidos
Campus de Viesques, 33271-Gijón (Asturias), Spain
eblanco@correo.uniovi.es

M T Stickland, T J Scanlon
University of Strathclyde, Department of Mechanical Engineering
Glasgow, G1 1XJ Scotland
mstickland@mecheng.strath.ac.uk

ABSTRACT.

This paper describes and old ironwork placed in a Spanish village. All parts of it are studied, specially the Air supply and the Hydraulic wheel. The minimum area in the water trump for a correct air flow is calculated. On the other hand, also the power supply by the hydraulic wheel, in normal conditions, to move the hammer with a required frequency is calculated.

KEYWORDS.

Air supplier, Water trump, Hydraulic wheel.

1.- INTRODUCTION.

There are documentary proofs of the existence since ancient times of iron industry in Asturias, a mountainous region on the northern coast of Spain with a very humid oceanic climate. In particular from the sixteenth to the eighteenth centuries many ironworks were raised throughout the region with the common characteristic of using the energy of the flowing water in rivers by means of hydraulic wheels. At first the hydraulic energy was utilised to produce the air currents needed by the furnaces and, after the sixteenth century, it was also used to drive the forging hammers. These ironworks were known as *ferrerías* in the regional language of Asturias.

Under the general designation of *ferrería* three types of installations, different but complementary, could actually be denoted: the *ferrerías* in their strict sense, the *mazos* and the *fraguas*. The formers were the establishments where the iron ore was melted and deoxidised to obtain iron bars. The *mazos* were the installations, usually adjacent to the *ferrerías*, where the iron bars previously obtained were continuously struck with a ram or a hammer to separate slag incrustations and to stretch and flatten the bars until achieving some preliminary shape. In the *fraguas* or forges, the last step of the process, the blacksmiths manufactured or repaired final iron products such as nails, pans, horseshoes, wheels, agricultural tools, etc.

In the seventeenth century those three stages of the production process were distinctively constituted at several sites of Asturias, particularly in the western region because of the abundance of rivers and the greater availability of the raw materials needed for their operation, namely iron ore and charcoal. The iron ore used to be extracted from small lodes at the surface of the terrain, which were usually placed at locations known only by the inhabitants of each zone. The charcoal had to be made in the woodlands from shrub roots or stumps and from chestnut or oak wood, both of them very abundant in the whole region. Sometimes the operation of the *ferrerías* had a seasonal character, due to the shortage of water in the rivers during summer.

Nowadays, there exist four *ferrerías* in Asturias in operation, after their restoration financially supported by the regional government of Principado de Asturias. One of them, called Mazo de Teixois, is described in this paper. It is located on the banks of the Mestas stream, at 3 km from Taramundi and very close to the border of Asturias with Galicia. This *mazo* is part of a very interesting ethnographic site related to the traditional uses of the hydraulic energy; it also includes a grain mill, a grinding stone, a mini-power plant and a fulling hammer.

2.- WEIR AND RESERVOIR.

The *ferrería* Mazo de Teioxis consists in a workshop building that contains a hearth, a power hammer and rooms to store iron ore and charcoal. Next to the building there is an elevated water reservoir, whose energy is used to move the hydraulic wheels and to produce a continuous air supply. Figure 1 shows a general scheme of the set up. Each of the installations is described separately below.

Fig. 1: Picture of facility

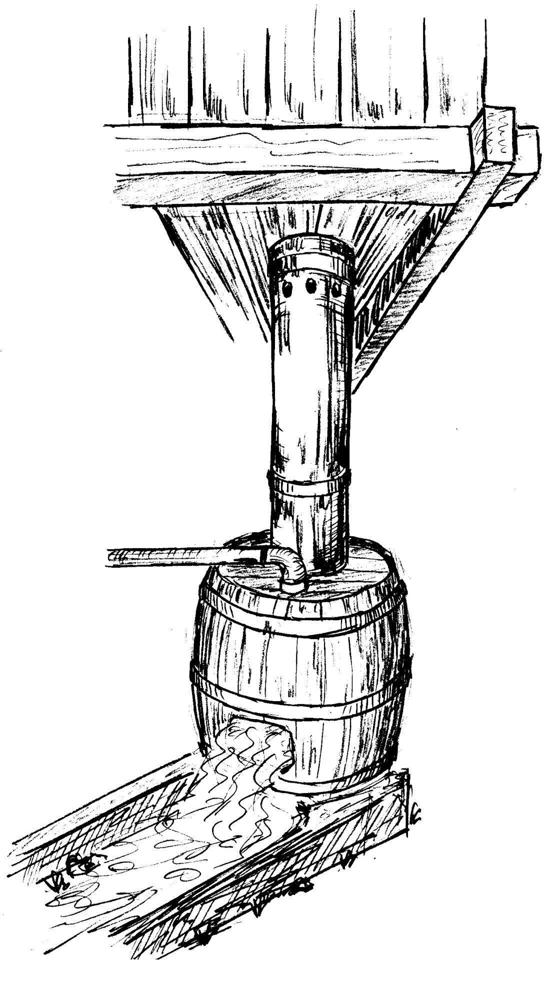

Fig. 2: Reservoir and Water trump

Weir.

Early hydraulic ironworks were located on the banks of the largest rivers, in order to make use of the natural velocity of the water currents. Subsequently artificial barriers were built across the rivers and brooks in order to store water with some amount of potential energy due to the increment of the free surface level. The weirs used to be erected at river locations with low velocity, from where a channel derived the water to the working site. At first the weirs were mostly wooden, by means of piling trunks with foliage across the riverbed, so that brunches dragged by the stream would be jammed and accumulated to the barrier. Later the weirs were also built with worked stone.

In the case of the Mazo de Teixois, water from the weir is conveyed along a channel worked across the hillside, with a length of 250 m. This channel has a rectangular cross-section of 0.75 m width. At the end of the channel there is a sluice gate to regulate the rate of water entering the reservoir at the ironworks site. Also, there are some spillways along the channel to prevent overflowing during very rainy periods.

Reservoir.

The water from the channel is collected in a wooden reservoir elevated 3 m with respect to the ironworks ground. Though this head is small, the corresponding accumulated hydraulic energy is enough to drive the hydraulic wheel. At the bottom of the reservoir there are two regulation orifices which may be progressively opened or closed by vertically displacing a wooden choke with a truncated cone shape at the lower end. Lateral guides ensure an axial shifting of the chokes with good alignment, so that the passage of water is eliminated when the valves are totally closed. These valves are driven from the interior of the *ferrería* by means of poles, so that both the rate of the air supplier and the speed of the rotating wheel (and hence the rhythm of hammering) can be easily controlled by the blacksmith. Figures 1 and 3 show some details of the elevated reservoir and the flow regulation valves.

3.- AIR SUPPLIER AND HEARTH.

Air supplier.

In the hearth of the *ferrerías* the temperature has to reach at least 1200 ºC, so that the iron becomes pasty and the slag get melted. A sufficient regular supply of oxygen was needed to reach such temperature and this has to be achieved by means of a mechanical air blower. The device used in the Mazo de Teixois consists in a *water trump*, a vertical pipeline that connects the elevated reservoir to a partially closed wooden tank located on the ground. When the water is flowing, the relative pressure at the pipe inlet becomes negative, so that air can be sucked in through a number of small holes available for such purpose. This air, very humid, is relieved from the water and accumulated in the upper zone of the ground tank, where the pressure is now positive. From this tank the air is then guided to the hearth through another wooden pipeline. This device provides a continuous supply of air with a high content of humidity, which is very convenient to deoxidise the iron ore, and so it was widely used in many ironworks. Figure 2 shows the external appearance of the air supplier. Figure 3 presents its cross-section, with indication of the geometrical variables that govern the air rate, and the nomenclature used for the different elements.

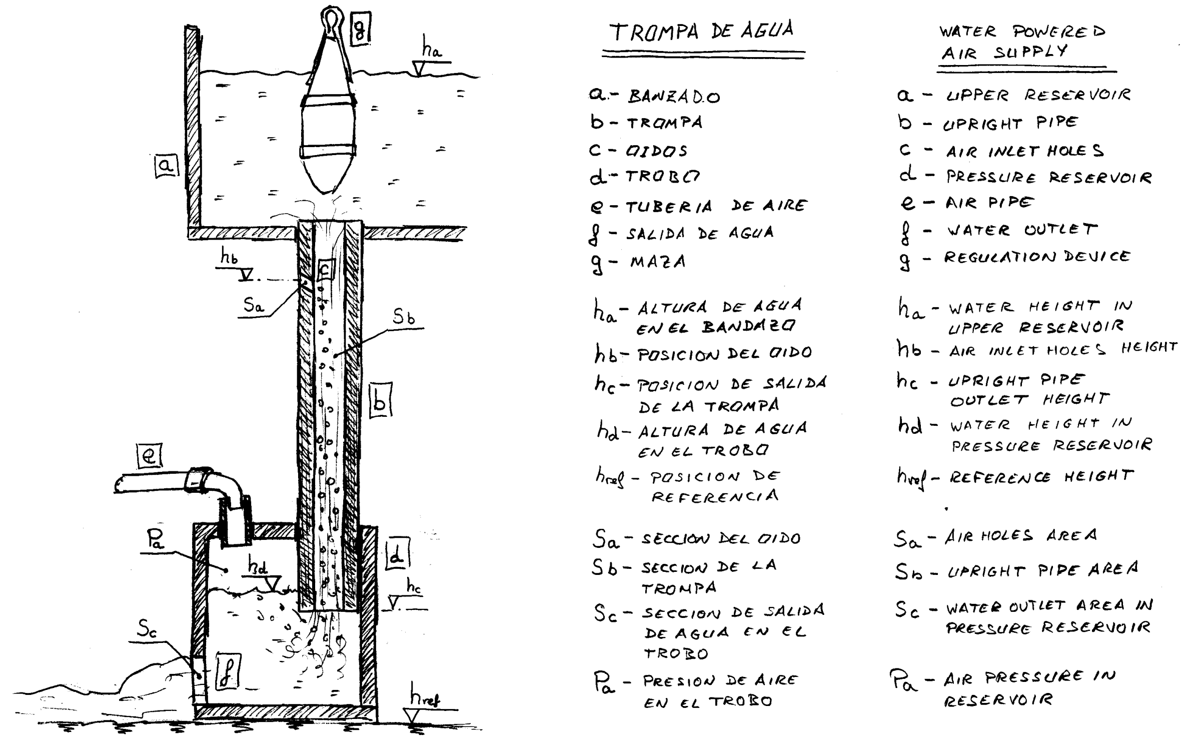

Fig. 3: Description of Water trump

The amount of air supplied by the *water trump* may be evaluated by applying fluid mechanics principles in a simple formulation as shown below.

Assuming operation in permanent regime and non-viscous flow, the air-flow supplied to the hearth is equal to the air-flow captured through the orifices at the pipeline wall, and it may be expressed as:

$$Q_a = S_a \cdot v_a \quad \text{(E. 1)}$$

The velocity of the in-coming air may be related to the local pressure in the pipe at the position of the holes, by establishing an energy conservation equation (Bernoulli´s) between an exterior point and the hole itself:

$$0 = \frac{P_b}{\rho_a \cdot g} + \frac{v_a^2}{2 \cdot g} \quad \Rightarrow \quad v_a = \sqrt{-\frac{2 \cdot P_b}{\rho_a}} \quad \text{(E. 2)}$$

Hence, the existence of flowing air requires a static pressure in the pipe at the orifice position, P_b below the atmospheric pressure. This negative relative pressure results from the gain of kinetic energy of the water when entering the vertical pipeline. Downwards the pipeline, however, the reduction of altitude makes the pressure increase till reverting positive, because the transverse section is constant. Several energy conservation equations may be used to relate the pressure of the air, for instance at the ground tank, P_a, to the geometrical dimensions of the device.

Between the upper reservoir and the vertical pipeline at the orifice position:

$$h_a = \frac{P_b}{\rho \cdot g} + \frac{v_b^2}{2 \cdot g} + h_b \quad \text{(E. 3)}$$

Between the upper reservoir and the outlet of the vertical pipeline:

$$h_a = \frac{P_c}{\rho \cdot g} + \frac{v_b^2}{2 \cdot g} + h_c \quad \text{(E. 4)}$$

Between the outlet of the vertical pipeline and the air trapped in the lower tank:

$$\frac{P_a}{\rho \cdot g} + h_d = \frac{P_c}{\rho \cdot g} + h_c \quad \text{(E. 5)}$$

Between the interior of the lower tank and its water outlet:

$$\frac{P_a}{\rho \cdot g} + h_d = \frac{v_c^2}{2 \cdot g} \quad \text{(E. 6)}$$

Also, mass conservation (continuity equation) implies that:

$$S_b \cdot v_b = S_c \cdot v_c \quad \text{(E. 7)}$$

By proper combination of the different equations, both the air flow-rate Q_a and the pressure P_a at the lower tank may be shown to be:

$$Q_a = S_a \sqrt{2 \cdot g \cdot \frac{\rho}{\rho_a} \left(h_b - h_a \cdot \frac{S_b^2}{S_b^2 + S_c^2} \right)} \quad \text{(E. 8)}$$

$$P_a = \rho \cdot g \left(h_a \cdot \frac{S_b^2}{S_b^2 + S_c^2} - h_d \right) \quad \text{(E. 9)}$$

It may be observed that, if the height of the upper reservoir is incremented then the air flow-rate Q_a reduces, but the pressure P_a of the air trapped in the lower tank increases. Also, the air flow-rate increases, with no effect on the pressure P_a, when increasing the height of the breathing orifice. Finally, the existence of air flow-rate is subject to the verification of the following relationship between heights and transverse sections:

$$\frac{S_c}{S_b} > \sqrt{\frac{h_a}{h_b} - 1} \quad \text{(E. 10)}$$

Hearth.

The hearth is the furnace where the ore is processed to obtain iron, and also, where the iron bars are conveniently heated to facilitate its shaping. In the hearth, the iron ore and the charcoal are arranged on several alternate layers; once the ore is melted the slag floats on the iron mass, which it is subsequently removed by hitting it with a hammer or a ram. The hearth is usually shaped like an inverted truncated pyramid.

4.- HYDRAULIC WHEEL.

In the Mazo de Teixois, the water stored in the upper reservoir (free surface at 3 m high) can be conveyed trough a wooden channel, when the corresponding regulation valve is open, towards the hydraulic wheel. The water impinges on some of the vanes of the wheel, producing a torque that makes the wheel rotate. This wheel is made of oak wood and has 16 vanes. The wheel has a diameter of 1.5 m and a width of 0.2 m. The vanes are 0.3 m long. The shaft of the wheel is made of oak wood, and it has a diameter of 0.6 m and a length of 5 m. The shaft is reinforced by a set of iron rings called *sellos*. The shaft is extended at both ends by a co-axial iron bar with a diameter of 0.08 m; each bar are vertically supported by a wooden framework that behaves like a bearing, since it permits the bar rotation with relatively low friction. At the end opposite to the wheel, the shaft has 4 fixed cams of 0.3 m long. When rotating, each cam pushes down the end of a beam that holds the hammer, which makes the hammer to lift up. When the cam loses contact with the hammer beam, the hammer falls down hitting the iron on the anvil. Cams and bearings are cooled and lubricated by a small water current so that wear is very small.

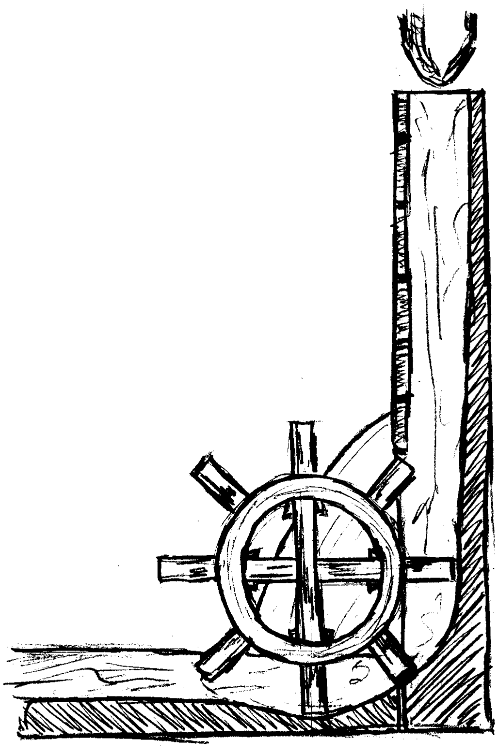

Fig. 4: Hydraulic wheel

In order to evaluate the torque that the wheel transmits to the hammer, a control volume that includes the wheel may be considered, with control surfaces perpendicular to the flow direction at both the inlet and the outlet. The flow velocity at the entrance of the turbine depends on the potential energy of the water at the upper reservoir. Assuming ideal flow, that velocity may be expressed as:

$$v = \sqrt{2 \cdot g \cdot h_a} \quad \text{(E. 11)}$$

The direction of this inlet velocity is tangential to the wheel. At the outlet, however, the fluid velocity has components in both the radial and the tangential directions. The radial component does not produce torque on the wheel axis and it is equal to:

$$v_r = v - \omega \cdot R \quad \text{(E. 12)}$$

in which ω is the rotation speed of the wheel and *R* the wheel radius. The tangential component is equal to the linear velocity of the wheel:

$$v_g = \omega \cdot R \quad \text{(E. 13)}$$

The law of conservation of the kinetic moment on this control volume may be formulated as:

$$\Sigma\vec{M} = \frac{\partial}{\partial t}\int_{VC}\rho\cdot(\vec{r}\Lambda\vec{v})\cdot dV + \int_{SC}\rho\cdot(\vec{r}\Lambda\vec{v})\cdot dQ \quad \text{(E. 14)}$$

$$Q = S \cdot v \quad \text{(E. 15)}$$

Since the regime is steady, the term of equation E.14 with a temporal derivative is zero. Hence, the torque transmitted to the hammer shaft under steady regime results to be:

$$\Sigma M = \rho \cdot R \cdot (v - \omega \cdot R) \cdot v \cdot S \quad \text{(E. 16)}$$

$$\Sigma M = 1000 \cdot 1.5 \cdot \left(\sqrt{2 \cdot 9.81 \cdot 3} - 1.5 \cdot \omega\right)\sqrt{2 \cdot 9.81 \cdot 3} \cdot 0.2 \cdot 0.3 = 690 \cdot (7.67 - 1.5 \cdot \omega) \quad \text{(E. 17)}$$

The power associated to that torque is:

$$P = M \cdot \omega \quad \text{(E. 18)}$$

The diagram of Figure 5 represents the torque and the power transmitted to the hammer shaft as a function of the rotational speed. The maximum power that can be extracted from the water is obtained for a flow inlet velocity that doubles the linear velocity of the wheel:

$$\left(\frac{dP}{d\omega}\right)_{\max} = 0 \Rightarrow \quad \omega = \frac{v}{2 \cdot R} \quad \text{(E. 19)}$$

For the Mazo de Teixois, that maximum power would correspond to a rotation speed of 2.56 Hz.

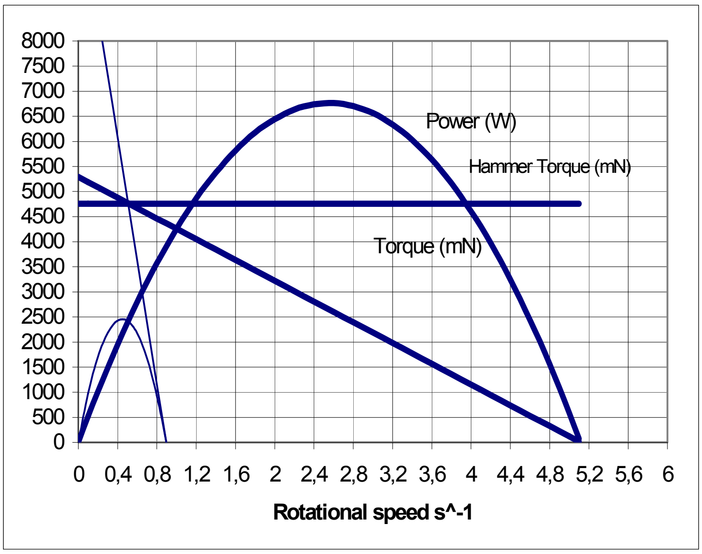

Fig. 5: Diagram of Power and Torque vs. Speed

5.- HAMMER.

The hammer is a crucial element in the traditional iron manufacturing processes. On one hand it is used to compact the iron in a bar and to remove the slag from it. On the other hand it is used for the stretching and smoothing of the iron bars, and, finally, to give these iron bars their definitive shape.

Figure 6 shows a sketch of the hammer at the Mazo de Teixois. This hammer is iron made and it weighs 200 kg. Its haft is of oak wood, with a length of 4 m and a diameter of 0.4 m. This beam is simple-supported at 2/3 of its total length from the hammer end. The hammer hits on an anvil with a truncated pyramid shape, which is clamped by a wooden stock buried underground.

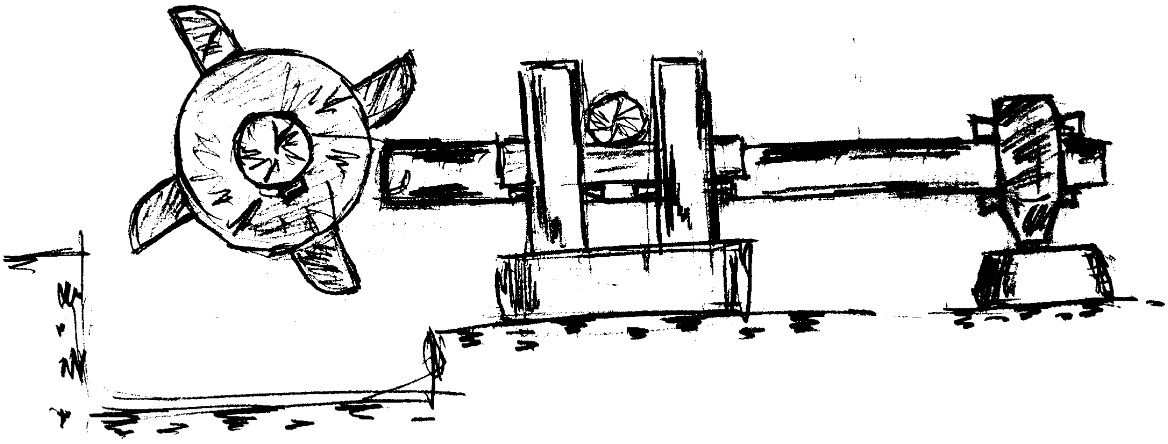

Fig. 6: Hammer

To lift the hammer, the force needed on the other end of the beam is:

$$F = \frac{200 \cdot 9.81 \cdot 2/3}{1/3} = 3924\ N \quad \text{(E. 20)}$$

Admitting an average radial distance of 0.8 m and a mechanical efficiency of 66 %, the torque needed on the wheel shaft is:

$$M = F \cdot l = 3924 \cdot 0.8 / 0.66 = 4756\ mN \quad \text{(E. 21)}$$

After comparison of equations E.17 and E.20, the rotational speed of the wheel results to be:

$$690 \cdot (7.67 - 1.5 \cdot \omega) = 4756 \quad \Rightarrow \quad \omega = 0.52\ s^{-1} \equiv 5\ rpm \quad \text{(E. 22)}$$

which corresponds to 20 hammer hits per minute. The real hammering rhythm is expected to vary between 18 and 25 hits per minute.

Hence the operating conditions of the wheel are well below the point of maximum hydraulic power transmission, because the device can produce the torque required by the hammer with the wished cadence only for a very small rotational speed. This means that the wheel is making use of only a small fraction of the hydraulic energy available in the incoming water. However, the poor efficiency of the process was not usually a real problem due to the abundance of water in the river course. Only during the summer period this ironworks could be forced to stop by the lack of sufficient water, which might have been helped by using a more efficient process. In order to use a wheel operating on its maximum power, a new wheel should be considered with a diameter of 14 m and squared vanes of 0.15 long; obviously this new wheel would hardly be feasible. Another possibility to improve the process efficiency would be to include a gearbox so that wheel and hammer shaft could operate with different rotational speeds. Given the techniques available at that time, however, a big wheel speed would generate an excessive friction torque as well as fretting wear at the bearings and gear teeth.

6.- CONCLUSION.

A description has been provided of the traditional ironworks powered by hydraulic energy in Asturias. Particular attention was paid to the ironworks called Mazo de Teixois, which has been recently restored into operation. The applications of the water energy to produce a permanent air current onto the hearth and to drive the working hammer have been analysed through the simplified formulation of fluid mechanics principles. The transformation of hydraulic into mechanical energy in this ironworks has been found to be a process with rather little efficiency, though more efficient solutions would not had been technically feasible at the time.

REFERENCES.

- Blanco, E. et al; "Sistemas de bombeo", Publicaciones de la ETSII Gijón. ISBN 84-604-9817-4, 1994.

- Fernández, J. et al; "Introducción a la Mecánica de Fluidos", Publicaciones de la Universidad de Oviedo. ISBN: 84-7468-969-4, 1997.

- Legazpi, J.; “Ingenios de madera”, Caja de Ahorros de Asturias, Oviedo 1991.

- Morís, G.; “Ingenios hidráulicos históricos: molinos, batanes y ferrerías”, Comunicación interna. ETSII – Gijón, Universidad de Oviedo, 1995.

- Sedille, M., "Turbomachines Hydrauliques et Termiques", Tome II, Masson & Cie, 1967.