

# Design and Numerical Analysis of Collimated Water Jet Cutting System

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**Abstract**—The Collimated Abrasive Water Jet(CAWJ) Cutting System is a compact system applicable in the workshop and on-site as well. The device allows machining between steam turbine discs with a gap space down to 120mm. The CAWJ Cutting System is supposed to overcome the main disadvantages of the conventional machine tool methods such as: long process times, lack of mobility of the drilling tools. For increasing the working efficiency and improving the cutting quality in material, the characteristics of the Cutting experiment and operating principle of a rig of CAWJ are discussed. Rock was cut for the experiment. The theory of abrasive accelerated in a long collimating pipe and reflect of cutting hard rock in various parameters of operating are analyzed. Theoretic and experimental results show that the CAWJ retains its ability basically when the length of the collimating pipe is in the range of 0.6m~2.8m. There is an optimum relationship during the length and diameter of the collimating pipe; abrasive feed rate and size. The research will lead to development of the hard rock cutting equipment using CAWJ.

**Index Terms**—Design, Collimated Water Jet Cutting System, collimating Pipe, Numerical Analysis, Cutting Rock

## I. INTRODUCTION

The tunneling systems of CAWJ have been put forward since later 80's. There are three steps for tunneling, first cutting deep contour slot using collimated abrasive jet cutter, then drilling deep holes using collimated drills, and last exploding. The new tunneling system has a lot of advantages, such as a lower tunneling cost and higher tunneling speed, a good rock laneway molding and supporting performance of rock wall, and a less embrasure needed.

CAWJ can retain its cutting power for distances of over 3 meter by collimating the abrasive jet in a pipe. So that collimated abrasive jets undoubtedly have further applications in mining, but such applications await an improved investigation of the theory and experiment of collimated abrasive jets.

## II. PIN CUTTER SYSTEM

The new system (Fig.1) developed to remove tight pins is using abrasive water jet cutting technology to weaken the pin in order to facilitate the removal. The main components of the system are a high pressure pump, cutting device, camera tool, abrasive feeder, clamping mechanism, catcher unit, suction system and a control unit.

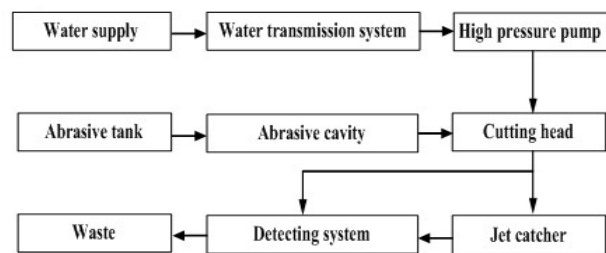


Figure 1. Components overview of the pin cutting system

### A. Water treatment and water pump

The water treatment can consist of a conventional mechanical filter system or in high standard water treatment system as used for system tests at the time being (details, please see datasheet [1]).

The high pressure pump consists of a hydraulic system, a high pressure water delivery system and a control system. The water is pressurized by a hydraulic system where the hydraulic oil pressure is acting on a piston resulting in a force on the plunger which pressurizes the water in the chamber.

For the installation requirements and any further product information please see the product documentation ESL Intensifier [2] and Model 30SA Intensifier Pump [3].

### B. Pin cutting device

The pin cutting device features two linear axes. The vertical z-axis consists of two spindles driven by servomotors and the horizontal x-axis is made up of an electromagnetically linear motor.

The tool fixture is mounted on the upper side of the linear motor. The tool fixture is used to either mount the camera tool for pin positioning or for the cutting head.

The pin cutting device is set up on top of the rotor between the rotor discs as shown in Fig.2. It is fixed after a rough positioning by two pneumatic cylinders. For pin positioning a digital camera is applied to align the cutting tool to the centre of the pin. The cutting head was developed particularly for this application because standard abrasive water jet components do not fit in the small gaps between rotor discs. The newly designed water jet cutting tool is patented by ALSTOM [4].

In the cutting head (Fig.3) an abrasive is mixed to a high velocity water jet resulting in an abrasive water jet feasible of cutting most technical materials. The catcher (patented by ALSTOM [5]) is mounted on the backside of the pin in order to absorb the remaining energy of the exiting water jet. Tungsten carbide bars in the inside of the catcher realize the absorption.

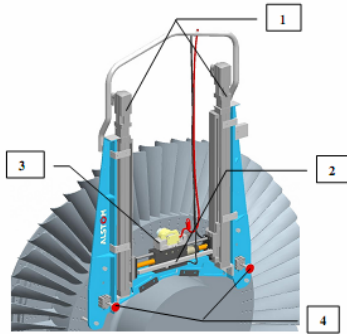


Figure 2. System set-up on the rotor

1- vertical z-axis, 2- horizontal x-axis, 3- tool fixture, 4- pneumatic cylinders

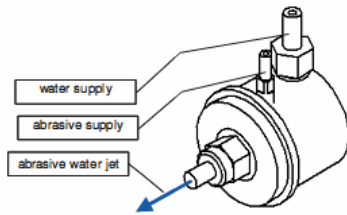


Figure 3. Cutting head

To reduce fog and dirt during machining, a suction system is connected to the unit. The suction system is a standard industrial wet vacuum cleaner [6]. Both the cutting device as well as the catcher has a connection to plug the cleaner. The cleaner is also controlled by the control unit. Most of the waste water produced by the water jet cutting process is collected by the suction system and pumped back to a waste water tank. The remaining waste water drains off without producing fog or splash and can be collected by a simple skip underneath the rotor. The working environment remains mainly clean. To remove the pin after weakening, a hydraulic jack can be used.

### C. Control unit

The control is based on an industrial computer with a programmable logic control (PLC) software. It actuates the several process steps and its graphical user interface (GUI) allows to locate the pin position. Due to the different geometries of steam turbine pins, several process parameters can be adjusted in a separate menu.

## III. FLOW ANALYSIS IN PIPE

A collimated abrasive water jet is a transient high-speed flow of multi-phase mixture in multi-dimensional direction and has a complex flow mechanism. So we suppose that ignoring the thermal exchange and thermal variety of collimated abrasive jets in the collimating pipe; ignoring the reciprocity among abrasive particles; considering the abrasive particles as ideal round balls; Ignoring the effect of pipe vibrancy on jets [7]. Considering that the multi-phase mixture is well-distributed fluid. Incorporating these assumptions, we can ignore pressure difference force, additional mass force, Basset force, gravity, Magnus force and Saffman force et al. The forces acted on an abrasive particle are apparent force and drag force between particle and water jets. The

Newton equation of an abrasive particle may be written as following

$$\frac{\pi}{6} d_p^3 \rho_p \frac{du_p}{dt} = C_d \cdot \frac{1}{2} \cdot \rho_c (u_c - u_p) \cdot |u_c - u_p| \cdot \frac{\pi}{4} d_p^2 \quad (1)$$

Or

$$\frac{du_p}{dt} = \frac{u_c - u_p}{\tau_v} \quad (2)$$

Where

$$\tau_v = \frac{\tau_{v0}}{f(Re_p)}; \quad \tau_{v0} = \frac{\rho_p \cdot d_p^2}{18\mu_c};$$

$$f(Re_p) = \begin{cases} 1 + \frac{1}{6} f Re_p^2 & (\text{where } Re_p < 1000); \\ 0.01767 Re_p & (\text{where } Re_p \geq 1000) \end{cases}$$

$$Re_p = \frac{\rho_c d_p |u_c - u_p|}{\mu_c}$$

The flow losses of the multi-phase mixture in the collimating pipe mainly include the drag loss between the mixture and interior wall of the collimating pipe, losses in the breakup region and in the backflow region. Experiments show that the breakup loss and backflow loss are 5 to 10 percent and 3 to 5 percent of total jet energy respectively when the jet speed is less than 500m/s.

The mass flow rate of the abrasive  $\dot{m}_p$  and mass flow rate of the liquid-gas mixture in all section of the collimating pipe keep constant, so the momentum equation of the abrasive and fluid mixture in the collimating pipe is written as

$$\dot{m}_c \cdot du_c + \dot{m}_p \cdot du_p = -dF_f - dF_i - dF_o \quad (3)$$

Where

$$dF_f = \pi D \cdot dx \cdot \tau_f$$

$$\tau_f = C_f \cdot \frac{\rho_f u_f^2}{2}$$

$$dx = u_c \cdot dt$$

Rewriting equation (3) gives:

$$\phi_c \cdot du_c + \phi_p \cdot du_p = -\frac{2}{D} \cdot C_f \cdot u_f \cdot u_c \cdot dt - \frac{dF_i}{\dot{m}_f} - \frac{dF_o}{\dot{m}_f} \quad (4)$$

Defining

$$du_m = \phi_c \cdot du_c + \phi_p \cdot du_p \quad (5)$$

We have

$$du_m = -\frac{2}{D} \cdot C_f \cdot u_f \cdot u_c \cdot dt - \frac{dF_i}{\dot{m}_f} - \frac{dF_o}{\dot{m}_f} \quad (6)$$

There are a lot of factors effecting on the drag coefficient between the multiphase mixture and the interior wall of the collimating pipe. The concrete method for calculating the drag coefficient of high-speed fluids is not available. Considering indeterminable and unpredictable factors, the drag coefficient can be written as

$$C_f = 0.6328 Re_f^{-0.25}$$

Then

$$u_p = u_m + (u_{p0} - u_m) \exp\left(-\frac{t}{\phi_c \tau_v}\right) \quad (7)$$

IV. EXPERIMENTAL ANALYSYS

Fig.4 to Fig.7 is calculating and experimental results. Experimental conditions are as following: pipe length  $L=1m$ , interior diameter  $D=15mm$ , pump pressure  $p_w=1000kg/m^3$ , water density  $\rho_w=1000kg/m^3$ , abrasive type=man-made carborundum, particle density  $\rho_p=3965kg/m^3$ , particle diameter  $d_p=2mm$ , abrasive feed rate  $\dot{m}_p=5kg/min$  target material of white marble and its hardness=11, stand-off distance=12.5mm.

The abrasive acceleration in the entrance of a collimating pipe is very high (shown in Fig.4, Fig.5). At abrasive feed rate of 2.7 kg/min, the 2mm- diameter particle speeds are up to 43 to 60 percent of the original water speed when abrasive particle move 0.5 meter in the pipe. But the 0.71mm-diameter abrasive particle speeds are up to 50 to 65 percent. The particle speed is the maximum and keeps length of a collimating pipe. The abrasive particles' acceleration is higher in thinner collimating pipe than in thicker one. The abrasive particle speed in the 10mm-diameter-collimating pipe is 40 percent higher than in 20mm-diameter collimating pipe when particles move 0.5 meter in the pipe. The abrasive speed increases to the maximum rapidly and then reduces gradually in thinner collimating pipes and but the abrasive particles accelerate at all times in thicker collimating pipes because the thinner the collimating pipes' diameter is, the greater the flow drag losses of fluids mixture are. The speed of 2mm-diameter abrasive particles is up to 64 percent of the original water speed, which is the maximum particle speed, when particles move 1.5 meter in the 10mm-diameter collimating pipe, and down to 45 percent of the original water speed at the exit of the pipe. But in the 20mm-diameter pipe, the particles' speed is up to 59 percent when particle pass 1.5m and up to 80 percent at the exit of the pipe. So thicker diameter is suit for longer collimating pipes and thinner diameter is suit for shorter collimating pipes.

The cutting performance of collimated abrasive water jets is becoming better and better with the pipe length increasing, such as the rock cutting depth and the erosion rate improving and specific energy decreasing (in Fig.6). But the cutting parameters have not an obvious variety in the pipe length range of 0.4 to 1.5 meter.

Fig.7 shows that the cutting depth decreases gradually, erosion rate improve, and the specific energy decreases with collimating pipe diameter increasing. If we want to get a large rock breaking volume, thicker diameter collimating pipes should be used. But if we want to get a deeper cutting depth, thinner diameter collimating pipes are need. Experimental results indicate that 12mm-pipe diameter is optimal in the conditions of this paper, which tallies with the theoretic analysis above.

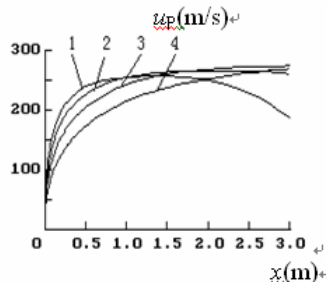


Figure 4. Calculated particle speed in the collimating pipe in the conditions of  $d_p=2mm, L=3m, D=1-10mm, 2-12mm, 3-15mm, 4-20mm$

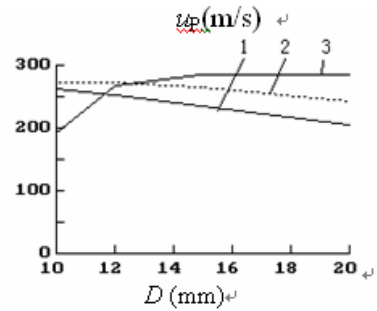


Figure 5. Calculated particle speed in the collimating pipe in the conditions of  $d_p=0.71mm, \dot{m}_p=2.7kg/min, L=1-0.5m, 21.0m, 3-3.0m$

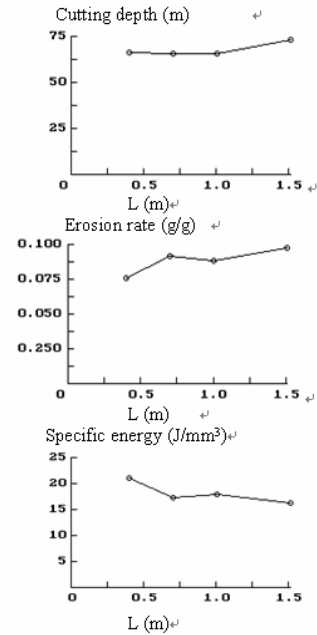


Figure 6. Effect of the length of the collimating pipe on cutting efficiency of CAWJ in the conditions of  $d_p=2mm, \dot{m}_p=5kg/min, D=15mm$

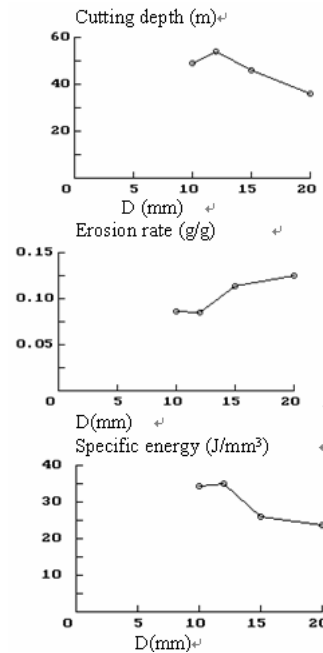


Figure 7. Effect of the diameter of the collimating pipe on cutting efficiency of CAWJ in the conditions of  $d_p=0.71mm$  and  $\dot{m}_p=2.7kg/min$

## V. CONCLUSION

The presented new technique to remove tight steam turbine pins offers a wide range of advantage compared to traditional drilling:

The machining time is massively reduced pin material influences are nearly eliminated by using abrasive water jet cutting; The system is made for mobile use so with suitable equipment the system can be used on site; The tunneling system of collimated abrasive water jets is a new-type cutting & drilling system that has the advantages of well laneway molding, strong ability of timbering wall rock and decreasing drilling hole quantity.

The abrasive particles are accelerated quickly in the entrance of the collimating pipe. The speed of 2mm-diameter and 0.71mm-diameter particles are 43 to 60 percent and 50 to 60 percent of the water original speed respectively. They basically are the maximum speed that the abrasive particles can get. The best pipe length is in the range of 0.4 to 3m for 15mm-diameter collimating pipe. There are three steps of accelerating and speed keeping and decelerating as abrasive particles in the pipe when the abrasive feed rates is great and particle diameter is small. So thicker diameter is suit for longer collimating pipes and thinner diameter is suit for shorter collimating pipes; If we want to get a large rock breaking volume, thicker diameter collimating pipes should be used. But if we want to get a deeper cutting depth, thinner diameter collimating pipes are need.

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