10. Water Droplet Erosion of Turbine Blades
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Research Activities on WDE

**WDE Model**
- Droplet impact theory
- Erosion mechanism
- Erosion parameters

**Secondary Effects**
- Performance degradation
- Vibration characteristics
- Stress distribution

**Erosion Protection**
- Moisture removal
- Erosion shield
- Surface treatment
- Advanced materials
- Increase of axial gap
- Smaller pitch diameter
Droplet Impact

Its Appearance or Applications

- Steam turbine blades
- Helicopter blades
- Aircraft and missiles travelling at high speed through rain
  - Historically, the erosion of steam turbine blades stimulated interest in the subject, but there is now considerable research on the rain erosion of aircraft and missiles, particularly the window materials.
- Coating: highly accelerated molten metal or ceramic droplets impact and bond on to a substrate
- Ink-jet printing
- Cutting of materials (using water jet)
- Spray cooling
- Cleaning of surfaces
During the initial stage of impact, liquid adjacent to the contact zone is highly compressed, whereas the rest of the droplet remains unaware of the impact.

This two regions are separated by a shock front which is also called as shock envelope.

When the contact edge velocity is higher than the sonic velocity, a shock envelope is produced.
During the initial stage of impact, the shock wave remains attached to the contact edge.

Later, a large density and pressure difference emerges across the free surface, and a strong jetting eruption starts at the contact edge.

The ‘jetting time’ is defined at the time when the liquid medium breaks through the droplet free surface at the contact edge.

This will occur when the contact edge velocity becomes equal to the shock velocity at the contact edge.

The jetting phenomenon could be related to the creation of breakup patterns.

Splashed liquid nickel droplet after impact (Impact velocity = 180 m/s)
Evolution of Density during Impact

FIG. 6. Time evolution of density during the droplet impact showing shock creation, propagation, and interaction with the free surface. The graph sequence correspond to times: (a) 7.98, (b) 18.04, (c) 38.04, (d) 56.98, (e) 95.58, (f) 109.33, (g) 123.24, (h) 138.94, and (i) 162.58 ns.

$V_n = 2.7 \text{ m s}^{-1}$
Droplet Impact Theory

Water-Hammer Pressure

- The pressure on the central axis after impact

\[ P_c = \frac{V \rho_1 C_1 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} \]

where, \( V \) is impact velocity, \( \rho \) is density, \( C \) is shock velocity, subscripts 1 and 2 mean liquid and solid, respectively.

- When the droplet impact on a rigid target, the pressure is frequently referred as “water-hammer pressure” and becomes:

\[ P = \rho_1 C_1 V \]

- The shock velocity is

\[ C_1 = C_0 + kV \]

where, \( C_0 \) is shock velocity (\( \approx 1647 \text{ m/s for water} \)), \( k \) is a constant having a value of 1.921.
Droplet Impact Theory

Water–Hammer Pressure

Impact Velocity = 500 m/s; \( d_p = 200 \, \mu m \)

Impact pressure profile at different times:
- 01.57 ns
- 03.25 ns
- 04.20 ns
- 08.15 ns
- 15.33 ns
- 23.76 ns

Diagram showing liquid drop and shock front formation.
The damage produced in a solid by the impaction of droplet may due to the impaction pressure, or to the shearing effects of the high-velocity radial outflow of the liquid, or to both.

Basically, initial stage of the damage is mainly caused by impact pressure, and radial flow plays a major role at later stages, after the surface is roughened.
Water droplet erosion has some similarities to continuous jet impingement ("jet-cutting"). However, there are differences, since the continuous jet produces stagnation pressure, whereas the discrete impacts in water droplet erosion produce much higher shockwave pressures.
**Water Jet Impact**

**Effect of Liquid Layer Thickness**

- Nozzle diameter = 2 mm
- Water jet velocity = 270 m/s
- Stand-off distance = 10 mm

![Graph showing the effect of liquid layer thickness on impact pressure](image)
1. Droplet Impact
2. Erosion Mechanisms
3. Erosion of Blades
4. Erosion Parameters
5. Reduction of Water Droplet Erosion
6. Flashing
The ductile materials undergo some amount of plastic deformation during water droplet impact.

Consequently, damage at early stages of erosion consists of shallow craters on the surface due to plastic deformation.

The accumulation of impacts with exposure time results in overlapping of impact craters and delamination of plastically deformed layers.

The progressive work hardening increases the probability of local fractures and leads to the detachment of thin platelets.

Source: Gerdes et al. (1995)
On the contrary, the materials having high hardness and low ductility increase crack sensitivity by reducing their capacity to plastic deformation.

Brittle materials, such as laser treated Ti-6Al-4V, are eroded by brittle fracture leading to formation of large flakes.

The accumulation of impingements results in the propagation of multiple subsurface cracks which can cause loss of bigger fragments when they cross together.

In spite of these effects of cracking, the erosion resistance of brittle materials is much higher than ductile materials.

This allows to suggest that strengthening provided by flame hardening or laser nitriding against droplet impact increases erosion resistance.

Source: Gerdes et al. (1995)
Erosion Mechanism

Erosion Stage

1. Incubation period
2. Acceleration period
3. Maximum rate period
4. Deceleration period
5. Terminal (final steady-state) period
Water Droplet Erosion

Erosion Stage

① **Incubation period**: in which there is little or no material loss. This may not appear if the impact conditions are severe enough to cause material loss for a single impact.

② **Acceleration period**: during which rate increases rapidly to a maximum.

③ **Maximum rate period**: where the erosion rate remains (nearly) constant.

④ **Deceleration (or attenuation) period**: where the erosion rate declines to (normally) 1/4 to 1/2 of the maximum rate.

⑤ **Terminal (or final steady state) period**: in which the rate remains constant once again indefinitely. However, in some tests, the erosion rate can continue to decline or fluctuate. Also, for some brittle materials, the rate can increase once again in what is called a “catastrophic stage.”
Erosion of steam turbine blade due to the impaction of water droplets causes serious problems, such as performance degradation, high maintenance cost, and low availability, in many power plants.

LSB erosion is the result of low velocity water droplets leaving the nozzle trailing edge and impacting on the suction side LSB leading edge.

- Therefore, hardened LSB leading edges are essential to reduce WDE.

WDE increases with higher moisture level, wheel speed, and lower pressure.

WDE can be reduced by improved moisture removal as follows:

- Improved moisture traps
- Hollow nozzle
- Grooved nozzles and buckets
Procedure of WDE

1. Fog Droplet Formation
2. Growth
3. Deposition
4. Atomization
5. Collision
6. Erosion

Condensation Shock

Water Film

Nozzle Blade

Fog Droplet

Droplet

Coarse Droplet Formation

Atomization

Steam Ws

Droplet Wd

Rotational Direction

Vd

Ws

V_s

U
Velocity Triangles

Cs: Absolute steam velocity
Ws: Relative steam velocity
Cd: Absolute droplet velocity
Wd: Relative droplet velocity
U: Peripheral rotation velocity

Nozzle

Bucket

Direction of rotation

Droplets
Water Droplet Erosion on LSB of 210MW Steam Turbine

(a) 8,785 h of turbine operation
(b) 20,489 h of turbine operation
(c) 56,384 h of turbine operation
(d) 82,910 h of turbine operation
Water Droplet Erosion on LSB

Eroded Leading Edge

Micrograph of an Eroded Surface
Classification of Erosion Severity

- **#2 Light**
  - $d = 0.005 - 0.015"$

- **#3 Light-Medium**
  - $d = 0.015 - 0.025"$

- **#4 Medium**
  - $d = 0.025 - 0.040"$

- **#5 Medium-Heavy**
  - $d = 0.040 - 0.080"$

- **#6 Heavy**
  - $d = 0.080 - 0.120"$

- **#7 Severe**
  - $d = 0.120"$ and above
Formation of Water Droplets

**Wilson Line**

- As the steam expands, it first releases its superheat energy until it reaches the saturated condition.

- Then, with further expansion, a portion of the latent heat contained in the steam is released. This conversion of latent heat introduces a state where water is formed in the expanding steam.

- However, heat transfer from the gas to liquid phase requires a finite period of time, and the expansion of steam in the steam path is extremely rapid.

- The elapsed time for steam entering a high pressure section to expand through it, and through the reheat and low pressure sections is about 0.2 seconds, if the time in the crossover pipes and the boiler reheater section is ignored.

- Because heat transfer cannot occur instantaneously, the expansion will continue under the saturated vapor line.

- At Wilson line, which is located approximately 60 Btu from saturated vapor line, heat transfer will have been completed and approach thermal equilibrium conditions, and moisture will form. This is the point where fog is formed, consisting of particles from about 0.5 to 1.0 microns in diameter.
Supersaturation = Condensation Shock

The Wilson line is located 60 Btu below saturated vapor line.

It was more precisely located by Yellot at a moisture of 3.2% compared to the 4% determined by Wilson.
Formation of Water Droplets

Cross Section of LP Turbine

- Supercooled Region
- Entry to Wilson Region
- Saturation Line
- Superheat Region
- Saturated Region
- Supercritical Region
- Droplet (seed) formation
- Water Droplet Erosion
- Fog Formation (Condensation Shock)
- Dry Steam
- Phase Change
- Wet Steam

Steam Turbine

10. Water Droplet Erosion
Formation of Water Droplets

Adhesion of Droplets on Blades

초기 물방울 생성 \( (d_p = 0.01 \mu m) \)

물방울 크기 급성장 \( (d_p = 0.2 \mu m) \)

물방울 크기 성장 및 수렴 \( (d_p = 1 \mu m) \)

Blade 표면에 부착 (전체의 5% 이하)

유막형성 및 뒷전에서 떨어져 나옴 (대형 물방울)

Discussion: Impulse vs. Reaction - which one is better in terms of water droplet erosion?
If a blade that has been in service in the wet steam region for an extended period is examined, there are often regions where the local depth of penetration by WDE is far greater than in the surrounding material.

This localized heavier erosion is caused by the occurrence of obstructions or collection points at different upstream locations within the steam path.

At these points moisture can collect or concentrate until it is suddenly torn off by the main steam flow, or thrown off by centrifugal action, causing heavy localized erosion on the following buckets.

This kind of heavier erosion is called as “concentrated” or “secondary erosion”.
Trailing Edge Erosion

Normal Rating Operation

Low Load Operation

Water spray

Turn-up Region
Trailing Edge Erosion

Water Sprays In the Exhaust Hood

- Water is sprayed into the exhaust hood in order to remove the windage heat, that is generated by frictional heating during part or light load operation and occurred in the lower half of last stage blade where re-circulation zone is formed.

- Normally, the treated water is used as the source of water and raw water is not used.

- The most common source is from the condenser hot well where there are unlimited quantities of relatively clean water.

- In spraying, the water is atomized, given as a wide distribution as possible, and a sufficient quantity is supplied to remove any latent heat from the steam.

- Unfortunately, this cooling water – if supplied in excess quantities more than required to remove the superheat - is left free in the exhaust hood.

- It is this free water that is captured by re-circulating steam and is carried back into the LSB.
Trailing Edge Erosion

[ Eroded Trailing Edge of LSB near the Hub ]

[ Recirculation in the Exhaust Hood ]

Water supply line

Water spray

Water running down casing walls

Recirculating steam

[ Source: 한전KPS ]
Trailing Edge Erosion
Trailing Edge Erosion

- Trailing edge erosion on the suction side
- Crack in the trailing edge caused by erosion - PT

A crack emanating from a trailing edge gouge
1. 기술지원 목표

브라질 Termonorte 복합발전소의 증기터빈에서 2004년 10월 발전소 자동정지와 동시에 심한 진동, 소음 및 화재가 발생하였다. 터빈 분해결과 최종단 회전식 64개중 17개가 파단 및 비산되고, #1 베어링의 절단, 고압터빈 고정식 및 회전식의 용융, 발전기 및 여가기가 심하게 손상되어 손상복구 비용이 180억원에 이르렀다. 사고 원인의 귀속에 따라 복구 비용이 부담됨에 따라 건설(현대), 제작(Fuji) 및 운 영회사(TNE, Elpaso)들은 원인분석에 충력을 기울 을다. 현대건설은 전력연구원에 사고 근본원인의 규 명, 해외 보험사 조사회의 참석, 제작사(Fuji) 사고 모델의 모순분석 및 기타 기술자문 등에 대한 기술 지원을 의뢰하였다.

- 터빈 분해결과 최종단 회전식 64개중 17개가 파 단 및 비산(Fig. 1)
- #1 베어링의 절단(Fig. 4)
- 고압터빈 고정식 및 회전식의 용융(Fig. 2, 3)
Turn-up Region에서의 사고사례

Fig. 6 LSB failure status

da. 운전이력
1) 상업운전 이후 발전소 운전이력
   - 전체 시간 : 9,928 시간
   - 기동 횟수 : 76회
   - 정지 시간 : 1,418 시간
   - 중간운전시간 : 8,510 시간
   - 30MW(25%) 이하 운전시간 : 1,538 시간(18%)

현재 전력사항으로 인해 같은 기동 정지 와 저출력 운전시간이 많았음

III. 결론

급변 브라질 발전소 터빈 사고분석은 근본원인에 따라 TNE(브라질), 현대건설 혹은 FUJI(일본)사가 손상복구비용을 전액 보상해야 하는 무담과 발전소 지분의 50% 이상을 갖고 있는 ELPASO(미국)사가 기술력으로 TNE를 지원하고, 현대건설에서 사고의 책임이 있다고 FUJI사가 주장하는 상황에서 전력연구원이 참여하였다. 사고원인 분석 결과 균열의 시작점은 저출력에 의한 Trailing Edge의 Erosion이며, 4회 이상의 저출력 + 고배압 운전에 의해 Stall Flutter가 발생되며 균열의 진전, 파단 및 비산으로 확산되었다. 균열 및 파단 배키니즘은 고주기파이며, #1 빠어림의 절단면에 따라 초기 사고가 크게 확대되었다. 사고의 근본원인은 운전미숙으로 인한 저출력 + 고배압 운전인 것으로 판단되었다.
1. Droplet Impact
2. Erosion Mechanisms
3. Erosion of Blades
4. Erosion Parameters
5. Reduction of Water Droplet Erosion
6. Flashing
Water Droplet Erosion

Erosion Parameters

An erosion model is essential to predict the life and performance of the turbine blades. A fundamental understanding of various erosion parameters is essential in order to develop an erosion model.

1. **Impact velocity**: there is “threshold” in which no material loss is observed at normal operating times. The dimensionless erosion rate varies as \((\text{impact velocity})^n\) where \(n\) is approximately 5, which is much higher than 2.

2. **Impact angle**: the water droplet impact angle has an effect on the erosion damage only up to formation of the erosion craters. Further progression of erosion is not affected by the initial impact angle of water droplets because the craters are formed parallel to the impact direction of the droplets.

3. **Droplet size**: the erosion rate (i.e. erosion due to a given amount of liquid) decreases with drop size. There is no obvious explanation to this phenomenon.

4. **Liquid density**: the erosion rate dependences of 2.0~2.5 power of liquid density.

5. **Hardness**: The harder the material, the smaller the erosion rate.
Water Droplet Erosion Test Facility

Nozzle Section

Test condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Inlet press.</td>
<td>0.03 Mpa</td>
</tr>
<tr>
<td>Inlet wetness</td>
<td>4%</td>
</tr>
<tr>
<td>Outlet press.</td>
<td>0.025 Mpa</td>
</tr>
<tr>
<td>Outlet steam vel.</td>
<td>300 m/s</td>
</tr>
</tbody>
</table>

Graph showing droplet erosion test results.
Water Droplet Erosion Test Facility

Bucket Section

Test Rig Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational Speed</td>
<td>max.15000(rpm)</td>
</tr>
<tr>
<td>Specimens Diameter</td>
<td>870(mm)</td>
</tr>
<tr>
<td>Impact Velocity</td>
<td>max.700(m/s)</td>
</tr>
</tbody>
</table>

Diagram:
- Spray Nozzle
- Atomized Air
- Specimen
- Vacuum Control Valve
- Rotating Disk
- Vacuum Chamber
- Condenser
- Water Drain
- Water
Test Materials

<table>
<thead>
<tr>
<th>Shield</th>
<th>12Cr Stainless</th>
<th>Ti-5Al-2.5Sn</th>
</tr>
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<tbody>
<tr>
<td>Stellite</td>
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<td></td>
</tr>
<tr>
<td>Ti-15Mo-5Zr-3Al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti-15Mo-5Zr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade</td>
<td>12Cr-Ni-Mo-V</td>
<td>Ti-6Al-4V</td>
</tr>
<tr>
<td>12Cr Alloy</td>
<td>Titanium Alloy</td>
<td></td>
</tr>
<tr>
<td>Material Type</td>
<td>Material</td>
<td>Vickers Hardness</td>
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<tr>
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<tr>
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<td>12Cr-Ni-Mo-V</td>
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<td></td>
<td>Stellite</td>
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<td></td>
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<tr>
<td></td>
<td>Ti-5Al-2.5Sn</td>
<td>295</td>
</tr>
</tbody>
</table>
1. Flow Rate

Rebounded droplets and water film thickness on the target surface should be investigated in terms of the flow rate of impacting droplets.

Droplet impact velocity = 568m/s
Sauter mean droplet dia. = 30.6 μm
It can be concluded that water droplet erosion rate is not affected by rebounded droplets and water film thickness.
In a typical cycling operation, the level of steam moisture varies significantly.

While the average steam wetness is not higher than 10~12 percent, the local steam wetness can be much higher, particularly in the tip region.

The higher the tip speed, the more dangerous the effect of the coarse-grained water that lags behind the steam.
1. Flow Rate
1. Flow Rate

Distribution of Wetness

\[ y_2 = 9.9\% \]

\[ y_2^{\text{max}} = 12.2\% \]
1. Flow Rate

Distribution of Wetness

I – rated operating condition
II – with decreased initial steam temp. $\Delta T = -60^\circ C$
III – with increased initial steam temp. $\Delta T = 60^\circ C$

Diagram showing the distribution of wetness with different operating conditions.
When the impact velocity is 629 m/s, the erosion rate reaches the peak in about 2 hours, thereafter the erosion rate decreases rapidly as the operation time increases and reaches a steady state.

As the impact velocity decreases, the peak of the erosion rate becomes lower and the time required to reach this peak becomes longer.

The erosion rate in the steady state period increases with impact velocity. This means that the erosion rate is a strong function of impact velocity.
2. Impact Velocity

Sauter mean droplet diameter = 30.6 μm
Impacted droplet flow rate = 6.2x10^4 kg/mm^2-h

\[ E = kV^5 \]
2. Impact Velocity

Blade Velocity vs. Blade Materials

![Graph showing blade velocity vs. blade materials.](image-url)

- Titanium Alloy
- 12Cr-Ni-Mo-V Steel
- 12Cr-Mo-V Steel
- 12Cr Steel

- **Blade Tip Velocity, m/s**
- **Active Length of Last Stage Rotor Blade, inch**

- **3600 rpm**
- **3000 rpm**
2. Impact Velocity

Threshold Velocity

![Graph showing the relationship between 
\( \Delta b, \text{mm} \) and \( \Delta l, \text{mm} \) as a function of \( \tau, \text{h} \).]
2. Impact Velocity

Threshold Velocity

![Graph showing the relationship between number of impacts and water jet velocity for different materials. The x-axis represents the number of impacts on the site, ranging from 1 to 400. The y-axis represents the water jet velocity in m/s, ranging from 100 to 600. The graph includes lines for Sapphire, Spinel, Si, and MgF₂, each representing a different material.](image-url)
3. Impact Angle

- The water droplet impact angle has an effect on the erosion damage only up to formation of the erosion craters.

- Further progression of erosion is not affected by the initial impact angle of water droplets because the craters are formed parallel to the impact direction of the droplets.

Impact Pressure vs. Impact Angle

- Impact Velocity = 270 m/s
- Nozzle dia. of water jet = 2 mm
4. Droplet Size

Droplet impact velocity = 568 m/s
Impact droplet flow rate = $6.2 \times 10^4$ kg/mm$^2$ -h

$E = k d^2$

$E = k d^{4.5}$
4. Droplet Size

Acceleration of Droplets

![Graph showing the acceleration of droplets with different symbols for different droplet sizes.]

- $\bar{V}_0/U_\infty$, $U_0/U_\infty$
- $X/Cx$ vs. $\bar{V}_0/U_\infty$
- Symbols:
  - $y = 0.25\%$
  - $y = 0.45\%$
  - $y = 0.96\%$
  - $y = 0$ (Air)

![Diagram showing the direction of rotation and droplet erosion.]

- Nozzle
- $Wd$
- $Cs$
- $U$
- $Ws$
- Bucket
- Direction of rotation

Steam Turbine

10. Water Droplet Erosion

56 / 99
4. Droplet Size

- The mean diameter of droplets decrease rapidly in the region from X/Cx=0 to X/Cx=0.05, as the slip velocity between stream and droplets becomes larger.

- Thus, the droplets travelling near the trailing edge are subject to the largest aerodynamic shear force so that the large droplets are broken up into smaller ones.

- The mean diameter of droplets near the trailing edge tend to increase with wetness under constant stream velocity.

from Tsubouchi et al. (1990), ASME PWR – Vol. 10
4. Droplet Size

Break-up of a Water Droplet

(a) Deformation of droplet kernel,
(b) Formation of joined boundary gas + liquid layer,
(c) Surface wave formation due to Kelvin-Gelmgolz instability,
(d) Surface wave formation due to Reoley-Taylor instability
Break-up of a water droplet by interaction with steam when Weber number is greater than 14

$$We = \frac{\rho V_r^2 d}{\sigma}$$

- $\rho$: density of steam
- $V_r$: relative velocity of steam
- $d$: droplet diameter
- $\sigma$: surface tension of water
5. Material Hardness

Droplet impact velocity = 568 m/s
Sauter mean droplet diameter = 30.6 μm
Impacted droplet flow rate = 6.2 x 10⁴ kg/mm²·h

Average erosion rate (mm³/mm²·h)

<table>
<thead>
<tr>
<th>Material</th>
<th>Erosion Rate (mm³/mm²·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure titanium</td>
<td>10⁻³</td>
</tr>
<tr>
<td>12Cr stainless steel</td>
<td>10⁻²</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>10⁻¹</td>
</tr>
<tr>
<td>Ti-5Al-2.5Sn</td>
<td>10⁰</td>
</tr>
<tr>
<td>Titanium alloy</td>
<td>10¹</td>
</tr>
<tr>
<td>Ti-15Mo-5Zr-3Al</td>
<td>10²</td>
</tr>
</tbody>
</table>

\[ E = kH^{-4} \]

\[ E = kH^{-2} \]
5. Material Hardness

- The erosion rate decreases as the hardness of blade materials increases.

- The erosion resistance increases approximately with the 2\textsuperscript{nd}~4\textsuperscript{th} power of material hardness.

- Erosion rate of 12Cr steel is proportional to the \(-4.2\) power of hardness.

- Erosion rate of titanium alloy is proportional to the \(-2.0\) power of hardness.

- The erosion rates of titanium alloys are remarkably lower than those of 12 Cr stainless steels, even if both materials have the same hardness. This is the reason why the titanium alloys are excellent blade material for longer last stage blades.

- Ti-15Mo-5Zr-3Al and Ti-15Mo-5Zr are superior in erosion resistance to Ti-6Al-4V, thus they are suitable for the erosion shield materials.
A Newly Developed Erosion Model:

\[ E = k \cdot f(m_d) \cdot g(V_d) \cdot h(d_d) \cdot j(H_{target}) \]

Where,  

- \( E \) = erosion rate, \( k \) = erosion constant, \( m_d \) = flow rate,
- \( V_d \) = impact velocity, \( d_d \) = droplet size,
- \( H_{target} \) = hardness of target material

1. The erosion rate is proportional to the flow rate of impacting droplet.
2. The erosion rate can be described by a power law of impact velocity. The mean value of velocity exponent for blade materials is reported to be approximately 5.0.
3. The erosion rate increases as the droplet size increases.
4. The hardness of blade materials is one of the important erosion parameters.
5. The effect of impact angle is ignored.
Calibration Results

\[
E = k \cdot \left( \frac{m_d}{m_{ref}} \right) \cdot \left( \frac{V_d}{V_{ref}} \right)^\alpha \cdot \left( \frac{d_d}{d_{ref}} \right)^\beta \cdot \left( \frac{H_{target}}{H_{ref}} \right)^\gamma
\]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Flow rate ( m_{ref} )</th>
<th>Impact vel.</th>
<th>Droplet size</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(x10^4 kg/mm^2-h)</td>
<td>( V_{ref} )</td>
<td>( V_{ref} )</td>
<td>( H_{ref} )</td>
</tr>
<tr>
<td>12Cr Stainless</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.06</td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td>Stellite</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.47</td>
<td>4.51</td>
<td></td>
</tr>
<tr>
<td>Pure titanium</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.09</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td>Ti-5Al-2.5Sn</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.20</td>
<td>4.60</td>
<td></td>
</tr>
<tr>
<td>Ti-15Mo-5Zr-3Al</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.20</td>
<td>4.60</td>
<td></td>
</tr>
<tr>
<td>Ti-15Mo-5Zr</td>
<td>6.2</td>
<td>568</td>
<td>30.6</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.20</td>
<td>4.60</td>
<td></td>
</tr>
</tbody>
</table>

The values underlined mean assumed ones.
1. Droplet Impact
2. Erosion Mechanisms
3. Erosion of Blades
4. Erosion Parameters
5. Reduction of Water Droplet Erosion
6. Flashing
1. Internal Moisture Removal

1) Water Catcher Belt

- Use of water catcher belt (collect slot).
- “A” is an axial gap to allow the moisture to enter.
- “S” is a distance between bucket centerline and moisture inlet centerline.
- “R” is a radial distance above the entry point and it is relatively large to prevent water rebound.
- “D” is depth of lips which are produced at the belt entry providing a drainage path for the collected water to drain to the bottom dead center where it can be removed.
- These designs are also arranged to have a steam blow-down of about 0.5% of the steam flow to help ensure effective removal of the water.
1. Internal Moisture Removal

1) Water Collection Belts
1. Internal Moisture Removal

2) Moisture Removal Groove Buckets

Cs: Absolute steam velocity
Ws: Relative steam velocity
Cd: Absolute droplet velocity
Wd: Relative droplet velocity
U: Peripheral rotation velocity

Nozzle

Droplets

Bucket

Direction of rotation
1. Internal Moisture Removal

2) Moisture Removal Groove Buckets

- **Moisture removal groove bucket**을 사용하여 ELEP에서 습분이 약 3.3%와 2.0% 감소

Enthalpy and Entropy increase by Moisture Removal

Saturated Vapor Line ($x=0$)

Expansion Line

Condenser Pressure

Quality Increase

$X_a$

$X_b$
1. Internal Moisture Removal

3) Suction Slots

Low Pressure Turbine
Droplet Impact Erosion Protection

Effective and proven measures against droplet erosion available

Reduction of water by:
- Extraction slots/drainage

Active protection by
Leading-edge hardening
(flame or laser hardening)

Reduction of water by:
- hollow stator blade with suction slots
- or heating of blade

Small droplets by
- axial gap design
- thin trailing edge

Suction slots
1. Internal Moisture Removal

3) Suction Slots

- Bleeding the boundary layer on the stationary blade partitions and draw away the moisture flowing there.

- This system has not been used extensively since results have rarely been found to justify the manufacturing cost.
1. Internal Moisture Removal

3) Suction Slots
1. Internal Moisture Removal

4) Slit

Last stage nozzle

MHI
40” LSB (Steel with stellite erosion shield)
Single cylinder single flow turbine, 122 MW (for combined cycle application)
2. External Moisture Removal

Quality in a Nuclear Steam Generator

<table>
<thead>
<tr>
<th>(Required) Quality</th>
<th>Calculated Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>① around 25 %</td>
<td>① around 25 %</td>
</tr>
<tr>
<td>② around 96~98 %</td>
<td>② 96 % (assumed)</td>
</tr>
<tr>
<td>③ should be higher than 99.75 %</td>
<td>③ 99.95 %</td>
</tr>
</tbody>
</table>
2. External Moisture Removal

토론: 원자력 재열사이클과 비재열사이클의 열효율 비교
1) 열역학적 관점
2) 실제적 관점
2. External Moisture Removal
3. Moisture Control

- Internal heating can be considered to reduce the moisture level at the last stage.

- However, this method has not been employed because of complexity.

- When the mechanical damage is occurred in the intermediate stage, moisture level at the last stage is decreased.

The effect of stage mechanical damage on wetness
Water droplet erosion rate is proportional to the amount of water impacting the blade.

Therefore, water droplet erosion is a function of moisture content at the inlet of the last stage nozzle.

If the condenser pressure is increased, there is a minimal change in the pressure at the inlet of nozzle.

Therefore, when the severe erosion occurs, there will be no advantage to increasing backpressure.

- $p_i$: pressure at the entrance of last stage
- $p_m$: pressure at the entrance of LSB
- $p_c$: condenser pressure
- $p_a$: increased condenser pressure
4. Erosion Shield

- Stellite has been widely used as erosion shield because it has a higher erosion resistance than 12Cr stainless steel.
- Simple design may have some degree of boundary layer separation, and efficiency loss from it.
5. Flame Hardening

- Erosion resistance of 12Cr stainless steel increases greatly with hardness.

- Flame hardening has been used popularly to increase erosion resistance in steam turbine blades.

- Flame hardening is undertaken using either direct flame impingement or induction heating of the blade material.

- With such a hardening system, process control is critical.

- At the transition HAZ (heat affected zone), there was a dramatic change of hardness.

BHN; Brinell Hardness
6. Titanium Blades

Price?

- Titanium alloys have higher tensile strength-to-weight ratio and superior corrosion resistance.
- Another benefit of titanium alloy blade is associated with greater resistance to water droplet erosion.
6. Titanium Blades

- As the turbine blade efficiency approach a plateau, increase of exhaust area for reduction in leaving loss appear to be the most attractive means of achieving higher efficiency without employment of more complex steam cycles or more advanced steam cycles.

- Conventional blade materials, such as 12Cr-Ni-Mo-V steel, cannot be applied for longer than 33.5 inch buckets for 60 Hz machines because of the lower strength-to-weight ratio.

- Titanium alloy has been applied as a base material for last stage blade of steam turbines because of its higher strength-to weight ratio.

- Although titanium alloys have higher erosion resistance than 12Cr alloys having same hardness, erosion problem should be solved because the droplet impact velocity increases with blade length.

- Recently, fine grain process has been developed to exclude attachment of erosion shield by Toshiba.

- Continuous market pressure to increase LSB length led developers to use titanium alloys instead of steel. Titanium alloys are less dense (1.8 times) and much stronger than steel, thus allowing the use of longer blades and larger annulus areas. (the yield strength of the Ti-6Al-4V titanium alloy is the same as 17-4pH steel, but the weight of titanium is only 57% of that steel).
6. Titanium Blades

- Ti-6Al-4V (fine grain process로 제작)
- 영흥 #1/2 : Toshiba 40” Titanium Blade, No Shield
- 영흥 #3/4 : Hitachi 40” Titanium Blade, Stellite Erosion Shield with EBW
- 신인천 #9/10/11/12 : 40” Titanium Blade
- 부산복합 : 40” Titanium Blade
- 포스코 광양 : 40” Titanium Blade
Corrosive pits at the shaft end sealing position of a rotor

Corrosive pits on the blades and covers

Caustic stress corrosion cracking
Boiling and high heat flux zones

IP Turbine
LP Turbine

Pitting – stress corrosion cracking, corrosion fatigue
(Causes: Cl, SO₄, CO₃, O₂, CuO, acetate, …)

2% Moisture
4%
6%
8%
10%
12%

Superheat
Condenser

Mollier Diagram for a Drum Boiler Cycle with Regions of Impurity Concentration
7. Laser Surface Treatment

The excellent high strength-to weight ratio and corrosion resistance of the titanium alloy Ti-6Al-4V has for many years highlighted it as an attractive material for aircraft and steam turbine design (L-1 row), but most important would be the advantage for the LSB of steam turbine substituting chromium stainless steels.

Although Ti-6Al-4V demonstrates a relatively high resistance to water droplet erosion, erosion is a still problem to be solved because the longer blades results in increased blade tip velocities.

In contrast to the 12% Cr steel the titanium alloys cannot be hardened to a great extent by quenching in order to improve the water droplet erosion resistance sufficiently.

Laser surface treatment has been studied to increase erosion resistance of titanium alloys.

In the case of titanium and titanium alloys, surface melting by laser in an atmosphere of N₂ gas results in the formation of a nitrogen rich surface layer (TiN dendrites).
7. Laser Surface Treatment

![Graph showing Mass Loss vs Erosion Time](image)

- Untreated
- Error Est
- Argon
- 10% Nitrogen
- 20% Nitrogen

**Axes:**
- Y-axis: Mass Loss (g)
- X-axis: Erosion Time (hours)
7. Laser Surface Treatment

![Graph showing Vickers Microhardness (HV 50) vs Distance from Surface (mm) for Laser Nitrided Zones at different temperatures.]

- a) Unannealed
- b) 650°C/4h
- c) 700°C/4h

The graph illustrates the Vickers Microhardness (HV 50) across different distances from the surface for three conditions: unannealed, 650°C/4h, and 700°C/4h. The laser nitrided zone is highlighted.
7. Laser Surface Treatment

![Graph showing cumulative volume loss vs. number of impingements for different materials.]

- 12%Cr steel/hardened
- Ti-6Al-4V
- TiN
- TiN+4h/650°C
- TiN+4h/700°C
8. Increase of Axial Gap

- One method of erosion protection is to increase the axial gap between the trailing edge of nozzle and the leading edge of bucket.
- The increased gap permits more time for the droplets to be accelerated to the velocity of the steam, reducing their velocity difference between droplets and steam.
- The smaller droplets, the longer axial distance between nozzle and bucket.
- This method is not employed extensively, because the cost of increasing the axial length is not so much beneficial compared to the potential gain from reduced erosion.
9. Smaller Pitch Diameter

- Smaller pitch diameter has been applied to reduce moisture at the last stage.
- However, longer LSB is favorable because it provides reduced leaving velocity, which results in low exhaust losses and improved heat rate.

<table>
<thead>
<tr>
<th>LSB Length (inch)</th>
<th>Frequency (Hz/rpm)</th>
<th>Pitch Dia. (inch)</th>
<th>Exhaust Annulus Area (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>60 / 3600</td>
<td>72.0</td>
<td>41.1</td>
</tr>
<tr>
<td></td>
<td>50 / 3000</td>
<td>91.0</td>
<td>51.6</td>
</tr>
<tr>
<td>33.5</td>
<td>60 / 3600</td>
<td>90.5</td>
<td>66.1</td>
</tr>
<tr>
<td></td>
<td>50 / 3000</td>
<td>99.5</td>
<td>72.7</td>
</tr>
</tbody>
</table>
1. Droplet Impact
2. Erosion Mechanisms
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5. Reduction of Water Droplet Erosion
6. Flashing
Flashing occurs when a high-pressure liquid flows through a valve or an orifice to a region of greatly reduced pressure.

If the pressure drops below the vapor pressure, some of the liquid will be spontaneously converted to steam.

When flashing is occurring, the flow is choked. That is the maximum possible flow is passing through the restriction at the given upstream pressure. This regime is also known as super-cavitation.

The only way to increase the flow is to increase the upstream pressure.

When this state is reached, the sound velocity in the two-phase mixture has been reached.

Therefore, droplets included in the two-phase mixture are accelerated rapidly.

The impact of the high-velocity liquid on piping or components creates flashing damage.

![Graph showing pressure variation with position](image-url)
Valve
Erosion Control in a Valve

Typical control valve. The high fluid velocity and low number of pressure reducing stages combine to produce insufficient stages to protect trim from cavitation erosion.
Erosion Control in a Valve

- $P_1$: Pressure
- $V_1$: Inlet velocity
- $P_V$: Flashpoint
- $V_2$: Outlet velocity
- $P_2$: Outlet pressure
Principle of Pressure Reducing Valve

High Pressure flow in

Expanded Low Pressure flow out
Surface Damage

Cavitation Erosion

![Graph showing pressure vs position with a label for vapor pressure.]

Cavitation erosion of a propeller

Steam Turbine

10. Water Droplet Erosion
Application of PRV
WDE of Titanium Tube in Condenser
질의 및 응답