Steam School Notes

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1 Injector Fundamentals: How Steam Lifts and Forces Water into a Boiler

1.1 What an Injector Does

> An injector uses steam from the boiler to force water into the boiler, against boiler pressure, with no moving mechanical parts.

An injector works because it converts pressure into momentum in the steam, transfers that momentum to water, and then converts it back into pressure.

1.2 The Intuition

If a hole is opened in the steam space of a boiler, steam escapes at very high velocity. Because steam is compressible, the pressure drop causes it to expand and accelerate until the flow becomes choked, after which the escape velocity is limited to approximately the speed of sound.

If a second hole is opened in the water space, water also escapes, but at a much lower velocity. Liquid water is effectively incompressible, so the pressure drop does work directly on the mass of water, converting pressure energy into kinetic energy according to Bernoulli's relation. The resulting velocity is set by the available pressure difference and the density of the water, and is typically only tens of metres per second.

Although steam and water escape at very different speeds, both openings experience the same boiler pressure. If the steam space and water space are connected together with a simple conduit such as a gauge glass, no sustained motion results. The pressures equalize, forces balance, and no mechanism exists to convert pressure into net momentum.

Replacing the gauge glass with an injector changes the situation fundamentally. An injector does not merely connect two regions of equal pressure; it forces steam to pass through a nozzle, deliberately converting pressure into velocity. The resulting high-velocity steam jet carries significant momentum. When this steam condenses upon contact with cold water, its velocity collapses and that momentum is transferred to the water. The combined jet then enters a diffuser, where velocity is converted back into pressure.

In this way, the injector exploits the different ways in which steam and water respond to a pressure drop. Steam supplies high velocity through compressible expansion, while water accepts transferred momentum and recovers pressure. A simple connection cannot produce motion because it transmits only pressure; an injector produces motion because it manufactures momentum and then recovers it as pressure.

(a) steam supply (b) injector & throttle (c) inlet

Fig. 1 Injector circuit

Fig. 1 shows how an injector is plumbed into the boiler.

a. steam supply from dome or wagon top with isolation valve
b. injector with steam throttle, water throttle and overflow check
c. inlet with inspection tee, isolation valve, check valve, and cheater

Steam is supplied from the dome or wagon top through an isolation valve. [@fig:figcic

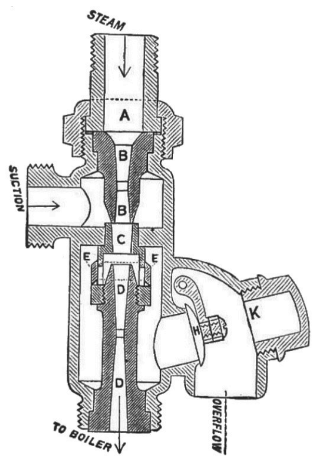

Fig. 2 Penberthy injector

Fig. 2 is cross-sectional drawing of a Penberthy steam injector, showing the internal flow paths and labeled parts:

A. steam inlet
B. Converging steam nozzle
C. Combining cone where steam entrains water
D. delivery cone leading toward the boiler
E. Overflow passages
F. K — Overflow valve assembly

The diagram illustrates how high-velocity steam from the top nozzle (A–B) creates a vacuum that draws water in from the suction side, mixes it in the combining cone (C), and then forces it through the delivery cone (D) into the boiler once condensation restores pressure balance. The overflow valve (K) vents excess water or steam during startup.

1.3 How the Overflow Check Valve Works

In Fig. 2, the overflow system consists of:

E — Overflow passages and H/K — Overflow valve assembly

This assembly is the injector's safety and priming system. It has one job:

> Let water/steam escape when the injector is not yet "picked up," but automatically close once the injector begins delivering water to the boiler.

Here's the sequence.

1. Startup: Steam enters the steam nozzle (A → B). When you first crack the steam valve: High-velocity steam shoots down the steam nozzle (A → B). This creates a partial vacuum in the combining cone (C). That vacuum begins to draw water from the suction side. But at this moment: The steam jet is not yet fully condensed. The mixture is chaotic: slugs of water,

slugs of steam. Pressure in the delivery cone (D) is nowhere near boiler pressure. So the injector cannot push water into the boiler yet.

2. The overflow valve is OPEN during this phase. Because the injector is not yet “working,” the pressure in the combining cone (C) and delivery cone (D) is:

    - below atmospheric, or
    - oscillating, or
    - not high enough to lift the boiler check valve

   So the overflow valve (H/K) stays open. This allows: - excess steam, - uncondensed steam, - water slugs, - or air to escape through the overflow passages (E). This is the “spitting” or “overflowing” you see when starting an injector. If the overflow valve did not open, the injector would never prime.

3. The injector “picks up” — condensation becomes complete. As the water flow stabilizes: The steam jet condenses completely inside the combining cone (C). This sudden condensation collapses the steam volume. The mixture accelerates through the delivery cone (D). Velocity is converted into pressure. At this moment, the injector transitions from “spitting” to “working.”

4. The overflow valve CLOSES automatically. Once the pressure in the delivery cone (D) rises above atmospheric: The overflow valve (H/K) is pushed shut by the pressure differential. The injec tor stops discharging through the overflow. All flow is now directed toward the boiler check valve. This is the moment when the injector becomes silent and smooth. The overflow valve is now acting as a check valve, preventing backflow.

5. If the injector loses its pickup, the overflow valve reopens. If anything interrupts the condensation process:

    - water supply falters
    - steam pressure fluctuates
    - scale or debris disrupts the jet
    - operator throttles incorrectly

   then the pressure in the delivery cone collapses. When that happens: - The overflow valve reopens - The injector begins “spitting” again The operator knows instantly that the injector has dropped out. This prevents boiler pressure from forcing water backward through the injector.

1.3.1 What happens if the overflow check valve is stuck closed when the steam valve is open?

In short, the circuit from steam to water becomes a closed loop, just like a gauge glass. Nothing moves.

1.3.2 Why does flow continue if it has started and the overflow check valve closes?

The boiler check valve opens and the overflow check valve closes because internal pressure is greater than atmospheric pressure. At this point, the injector is no longer a steam jet device; it is a pure water pump powered by the collapse of steam volume. And pumps do not need an open discharge to atmosphere.

1.4 The Three-Nozzle System

An injector has three functional stages:

- Steam nozzle
    - Expands steam to very high velocity (hundreds of m/s)

  - Steam jet entrains surrounding water
- Combining cone
  - Steam condenses inside the water stream
  - Momentum of the mixture increases
  - Pressure begins to recover
- Delivery cone
  - Converts velocity back into pressure
  - Final pressure exceeds boiler pressure
  - Water flows into the boiler

1.5 Velocity of water

Water escaping from the water space of a boiler is reduced in pressure. Bernoulli's relation expresses the conversion of pressure energy into kinetic energy: a pressure drop does work on a fluid, and that work appears as velocity, scaled by the mass density that must be accelerated.

We are working with bar as a unit of pressure, but bar is not a base-unit in SI. To convert bar to SI, we need conversion that looks like this:

$$bar_{si(P)} \to P\,\mathrm{bar} \cdot 100000\,\frac{\mathrm{kg}}{\mathrm{bar\cdot s^2\cdot m}}$$

Now Bernoulli's relation can be expressed as

$$v_{water}(P) = \sqrt{\frac{2\Delta_P}{\rho}} \text{ where } \begin{cases} \Delta_P \to bar_{si}(P)\,\frac{\mathrm{kg}}{\mathrm{m\cdot s^2}} \\ \rho \to 1000\,\frac{\mathrm{kg}}{\mathrm{m^3}} \end{cases}$$

and $$\begin{aligned} v_{water}(8) &= v_{water}(8) \\ &= 40\,\frac{\mathrm{m}}{\mathrm{s}} \end{aligned}$$

The resulting water velocity is small compared to steam velocity because liquids store pressure energy primarily as mass acceleration rather than compressible expansion.

1.6 Velocity of steam

At 100–150 psig:

- Saturated steam specific volume: ~0.2–0.3 m³/kg
- Speed of sound: ~450–500 m/s
- Nozzle exit velocity: 300–500 m/s

The steam supply nozzle of an injector operates under choked-flow conditions. As steam expands from boiler pressure, its velocity increases until it reaches the local speed of sound, beyond which further acceleration is impossible. The steam therefore enters the injector at approximately sonic velocity, providing the high momentum needed to entrain feedwater.

1.7 Condensation as a Power Source

Inside the combining cone:

- The steam jet condenses into the water
- The steam's enormous volume collapses
- Momentum is conserved
- The mixture's pressure rises sharply

This is why injectors can deliver water above boiler pressure.

1.8 Operating Sensitivities

Injectors depend on:

- Correct steam pressure
- Adequate water supply
- Clean cones
- Proper temperature (too hot → injector fails)
- No air leaks on the suction side

These sensitivities all trace back to the same physics: steam velocity, condensation, and momentum transfer.

1.9 Linking Back to Boiler Heating

The injector relies on the same physics as the rapid pressure rise when a boiler reaches the boiling point:

- Steam has enormous specific volume
- Steam accelerates to extreme velocities
- Condensation collapses that volume
- Pressure is recovered from velocity

The boiler's rapid pressure rise during boiling is the "other side" of the same phenomenon.

2 Low-Pressure vs High-Pressure Steam Injectors

2.1 Definitions

- **Low-pressure injector**: Designed to start and operate with **low boiler steam pressure**.
- **High-pressure injector**: Designed to operate efficiently at **high boiler steam pressure**.

  The terms refer to the **boiler steam pressure range the injector can work over**, not the pressure delivered to the boiler.

2.2 Low-Pressure Injectors

2.2.1 Typical Pressure Range

- ~15–80 psi (sometimes up to ~100 psi depending on design)

2.2.2 Design Characteristics

- Larger steam nozzle
- Larger combining cone
- Larger water passages
- Gentler cone angles

2.2.3 Operating Characteristics

- Easy starting at low pressure
- Tolerant of cold feedwater
- Tolerant of minor scale or dirt
- Less sensitive to adjustment

2.2.4 Limitations

- Inefficient at high pressure
- Tendency to overflow above design pressure

2.2.5 Typical Applications

- Early locomotives
- Traction engines
- Stationary boilers
- Systems with slowly rising boiler pressure

2.3 High-Pressure Injectors

2.3.1 Typical Pressure Range

- ~125–300+ psi (design dependent)

2.3.2 Design Characteristics

- Smaller steam nozzle
- Tighter combining cone throat
- Sharper delivery cone geometry
- More precise internal dimensions

2.3.3 Operating Characteristics

- High efficiency at rated pressure
- Smooth delivery at high boiler pressure
- Minimal steam waste once running

2.3.4 Limitations

- Difficult or impossible to start at low pressure
- Sensitive to:
    - Warm feedwater
    - Scale or dirt
    - Incorrect nozzle sizing

2.3.5 Typical Applications

- Later steam locomotives
- High-pressure stationary boilers
- Marine boilers
- Systems with steady operating pressure

2.4 Comparison Summary

Feature	Low-Pressure Injector	High-Pressure Injector
Starting pressure	Very low	Moderate to high
Steam nozzle size	Large	Small
Dirt/scale tolerance	High	Low
Feedwater temp tolerance	Good	Poor
Efficiency at pressure	Lower	Higher
Ease of starting	Easy	Difficult

2.5 Common Locomotive Practice

- Two injectors often fitted:
    - **Low-pressure injector** for starting and low-pressure operation
    - **High-pressure injector** for efficient running at road pressure

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2.6 Key Principle

Injector pressure range is fixed by geometry:

- Steam cone diameter
- Combining cone throat
- Delivery cone shape

Changing pressure range requires **changing nozzles**, not valve adjustment.