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Fluid mechanics of needle valves with rounded components Part I: Configurations and models

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ABSTRACT

This is the first part of a trilogy that reports the results of combined experimental and computational investigations of fluid flows in the active space of needle valves – the configurations of which are characterised by rounded needle tip or exit channel entrance or both. Interest in these rounded shapes arose recently due to planned needle valve applications for very high temperatures and possibility of erosion by aggressive hot fluids, endangering the valve by rapid deterioration. This Part I discusses mainly the geometry of the problem and configurations of the models used in the tests reported in subsequent Parts I and II.

1. Introduction

Needle valves are devices serving for fluid flow control in response to a mechanical input (which, in turn, is often derived from an electric input signal). The control action is achieved by varying the cross section area available for the flow. The component performing this variation is an axially movable body the tapered end of which occupies the space in the entrance into exit channel. The accuracy of this control is increased if the taper angle is small – top of Fig. 1. Also, most applications having been always in small size of the movable body, and the resultant shape resembling a sewing needle has resulted in the commonly used name.

This flow control valve idea has been known and used since the prehistory of engineering. In contrast to most other valve configurations, the fluid flow is in the needle valves not forced to change drastically the direction of its motion. Thus, with suitable design – an example of which is in the bottom part of Fig. 1, the overall hydraulic loss in the open valve regime may be quite small. It was mainly this low loss property that has led to documented earliest uses, very often in the role of adjustable nozzles [1]. Such nozzle generates a fluid jet issuing from the valve exit channel – similarly as it does so in fixed-geometry nozzles discussed in [2]. It was in this role of adjustable-property nozzle that needle valve was used by Giffard [3] in 1858 in his jet pump for railway steam engines. Similar adjustable nozzle role was also used in Pelton turbines [4].

Literature reports, e.g. in [11], a demonstrated capability of the needle valves with small apex angle of the needle to dispense measured fluid amounts with accuracy better than pico-litre level. Present-day designs for use with an electro/mechanical transducer tend to chose large angles, resulting in faster flow rate response. Thus there are currently quite common “needles” with the apex angle β as large as the 90° shown in Fig. 2 or even more, thanks to currently available high precision needle moving actuators.

2. Increasing interest in fluid mechanics of needle valves

Characteristic general feature of engineering is continuing request for high speed of systems and devices operation. Valves for fluid flow control are no exception; many applications demand fast adjustment of the flow rate. The speed necessitates reducing the mass (and hence inertia) of all moving components. This trend, especially in electrically controlled valves, has recently led to an increased interest in needle valves with their typically small (i.e. minimum mass) single moving component, the needle. In contrast to the long taper designs (top part of Fig. 1) which are common in valves for precise manual adjustments, the fast electrically controlled valves demand short needle travel. Apart from the resultant low acceleration, one of the reasons behind the short travel (obtained with the large apex angle β) are the short movements of piezoelectric drive types.

In the manually operated valves there is little reason for study in detail the internal flowfield. The only design demand apart from the precision are small hydrodynamic forces to overcome, which is

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Nomenclature

c_P	Pressure coefficient [–]
d	Exit channel diameter [m]
F	Dominant cross section area [m^2]
l	Exit channel length [m]
$\dot{M}$	Mass flow rate [kg/s]
P	Pressure [Pa]
ΔP	Measured pressure difference [Pa]
r	Entrance rounding radius [m]
r_C	Needle tip rounding radius [m]
Re	Reynolds number [–]
v	Specific volume [m^3/kg]
w	Reference velocity [m/s]
X_1	Distance along exit channel [m]
X_{1C}	Distance along needle end [m]
z	Needle lift [m]
β	Cone apex included angle [–]
φ	Area ratio [–]
ρ	Relative entrance radius [m]
ρ_C	Relative needle tip radius [m]
λ	Exit channel relative length [–]
ξ_1	Relative distance along channel [–]
ξ_{1c}	Relative distance along needle [–]
ζ	Relative lift [–]
ζ^*	Upper lift limit [–]

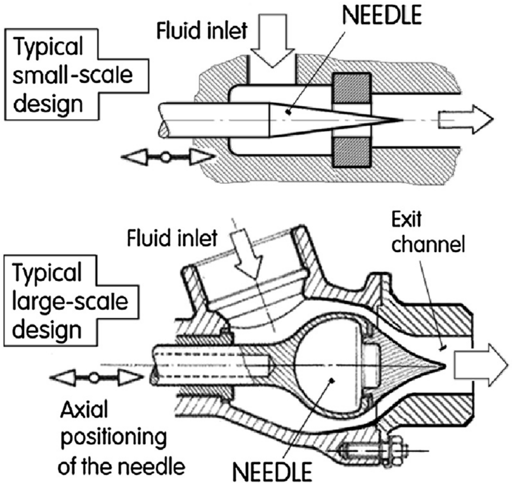

Fig. 1. Examples of typical needle-valve designs. Top: Scaled-up drawing of a small version. The thin rod with the sharp tapered end gave rise to the "needle" term. Bottom: Valve controlling large flow, in the key design factor of which was low hydraulic loss in the open regime.

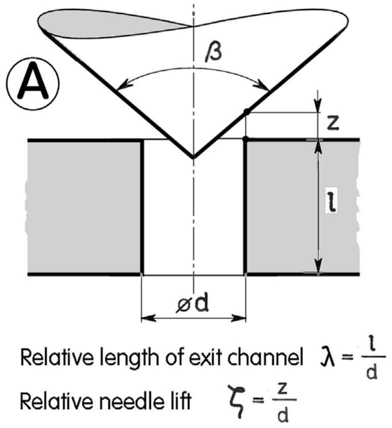

Fig. 2. Sharp edge and sharp tip valve version A investigated in [5] was the starting point for the rounded geometries.

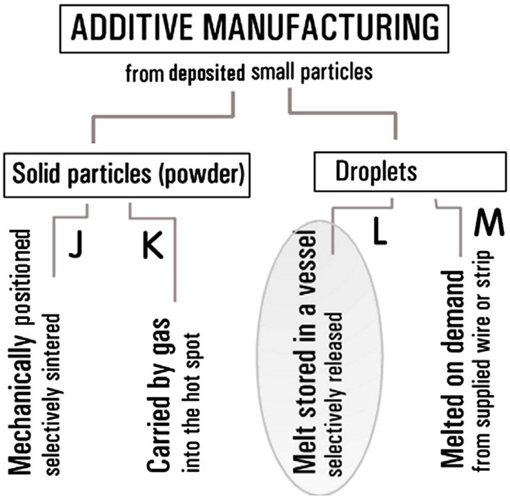

Fig. 3. The application that has recently led to renewed interest in needle valves: additive manufacturing branch L with selective release of molten material from a heated container.

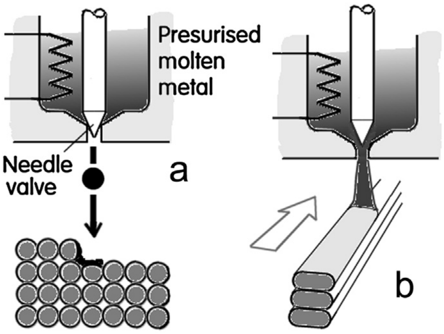

Fig. 4. Small added molten-metal volumes (required for quality of resultant surfaces) tend to slow the manufacturing progress. Solution are fast response valves. (a) Schematic representation of the addition to the manufactured product of individual drops. (b) Addition of narrow strips may be faster – but not always applicable.

hardly any problem. Different situation is with the demands of the fast electric control. The hydrodynamic forces acting on the needle fast changing its position may be significant, especially mainly when operating with liquids (or course, the more so when the liquid is molten metal – Figs. 3 and 4). The flowfield may contain details with complex flow configurations (especially due to flow separation from the walls, as it was encountered e.g. in [5]). These are reasons leasing to increased application of numerical flowfield computations. Nevertheless, so far existing computation results in literature are rare and often deficient in extent and quality. Really contributing to the existing knowledge are only few recent references, such as e.g., [1,5]. To reduce the number of variables to be handled in these studies, the solutions and analyses were usually done with simplified geometries. Typically, the geometry investigated in [5] – here shown in Fig. 2 – is characterised by straight-line contours, i.e. with sharp tip of the needle cone and also sharp edge of the inlet into the exit channel.

Valves discussed as the subject in the present article are characterised by replacing the sharp features of [5] by rounded, constant-radii shapes. Admittedly fully corresponding to practical valve geometries, but more realistically responding to the demands