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Analysis of the water supply system of the city of Apamea, using Computational Fluid Dynamics. Hydraulic system in the north-eastern area of the city, in the Byzantine period

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Abstract

In this paper, the flow of water in several elements of the water supply system of the city of Apamea (Syria) is simulated. The studied elements were used in the 6th century AD (Byzantine period). These simulations allow a modern point of view analysis of the water supply system, in terms of water flow rate, energy loss, decanter efficiency, … This analysis provides a qualitative description of the water supply system of the city, supplementing the field observations.

Keywords: Hydraulics; Computational fluid dynamics; Water supply; Apamea; Aqueduct

1. Introduction

The archaeological site of Apamea in Syria, on the right bank of the Orontes, between Hama and Alep, had a continuous human activity that can be tracked back to the Middle Palaeolithic. After the conquest of Alexander the Great, Seleucos Nicator, Greek king of Syria, established there a Greek city in 300/299 BC.

Apamea became one of the main cities of the Seleucid Empire, with Antioch, Seleucia or Laodiceia. Apamea imposed itself as an administrative and military centre of North Syria and reached its broadest development during the Roman and Byzantine periods. Because of several violent earthquakes, the city was characterized by large reconstructions, which have sometimes profited from liberalities of Roman Emperors.

Capital of the Roman province of Syria Secunda, densely populated, Apamea reached a real prosperity during the 5th and 6th centuries AD until Persian Wars and dramatic earthquakes made the city weak and vulnerable to the Arabic conquest in 638.

Since the beginning of the 2nd century AD at least, a large street with porticoes offered to the city a monumental artery by which the town was intersected from North to South. This Cardo Maximus, about 37 m wide and 1850 m long, was also used for wheeled transport during the Roman period. A second feature of urbanism was the large wall that enclosed the city. The foundations of this about 7 km long fortification were set in the Hellenistic times. The only known water supply of the city is an aqueduct, used from 47/48 AD [3] until the 7th century at least. It was bringing water into the town from a spring located about 80 km from Apamea [2].

Excavations in the north-eastern area of the city, where the aqueduct goes into the town, were performed in the last four years by the team of Prof. Viviers from the Université Libre de Bruxelles. They revealed at least four main periods of (re)-construction, characterized by different water systems [14]. The latest one was built at the end of the 4th century AD or the beginning of the 5th and was used until the 7th century (Period IV). This fourth period is itself divided in four sub-periods by the archaeologists.

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Notation

b	width of the inner aqueduct (m)
C	energy drop coefficient, $kg^{-1}\,m^{-1}$ or $kg^{-1}\,m^{-2}$ when the energy drop is expressed per unit length of a canalisation
E	energy of the flow, expressed per unit volume of water ($kg/(m\,s^2)$)
ΔE	energy loss, $kg/(m\,s^2)$ or $kg/(m^2\,s^2)$ when the energy drop is expressed per unit length of a canalisation
g	gravity acceleration (m/s^2)
h	height of water in the inner aqueduct (m)
H	see Fig. 7 (m)
k	turbulent kinetic energy (m^2/s^2)
K	roughness of a wall (m)
n	Manning coefficient ($m^{1/6}$)
p_{atm}	atmospheric pressure ($kg/(m\,s^2)$)
P	statistical average of the pressure ($kg/(m\,s^2)$)
Q	mass flow rate (kg/s)
Q_{max}	maximum flow rate that can be carried by a derivation (kg/s)
U_i	statistical average of the ith component of velocity (m/s)
U_p	statistical average of the velocity magnitude at the centre of a cell adjacent to a wall (m/s)
t	time (s)
V_{aq}	mean velocity in the main direction of the flow in the inner aqueduct (m/s)
x_i	ith Cartesian coordinate (m)
y_p	distance between a wall and the centre of a cell adjacent to this wall (m)
z	height (m)

Greek letters

ε	dissipation rate of the turbulent kinetic energy (m^2/s^3)
ν	kinematic viscosity (m^2/s)
θ	$\tan(\theta)$ is the slope of the inner aqueduct
ρ	volumetric mass of water (kg/m^3)
Ω_{in}	area of the section of the connection between the aqueduct and a room of visit (m^2)

Subscript

aq	inner aqueduct
b	bend
c	canalisation
cit	cistern at the end of the first derivation
in	beginning of a derivation
r	room of visit
out	end of a canalisation

In Fig. 1, the excavated hydraulic installations in the north-eastern area of the city are sketched. Arrows represent the flow of water in the system during the late Byzantine period (Period IV c). The main elements of the hydraulic system in this period are numbered in Fig. 1. The ancient aqueduct (point 1) is blocked at point 2 and the water is derived into a large cistern in a guard tower. The construction date of this cistern is not precisely known, but it was built at least in the beginning of the 5th century, and probably in the 3rd. From this cistern, the water is carried by an inner aqueduct (point 3 and Fig. 2), roughly oriented North–South, parallel to the Cardo Maximus, along the second East street. From point 4, the covering blocks are missing. An observation hole is attested at point 5 (see also Fig. 2). From this inner aqueduct, several derivations are performed.

A first derivation occurs approximately 10 m after the beginning of the aqueduct. It is mainly composed of a canalisation made of the fitting of basic pipes into each other. Just after the beginning of the derivation, a room of visit is observed (point 6 and Fig. 3). The connection between the aqueduct and the room of visit is dug through the aqueduct wall. It is 34 cm long and has a rectangular section of $19 \times 10\ cm^2$. The first pipe of the canalisation is connected to this room. This derivation carries water into a second cistern. A 90° bend is observed at point 7. It is realized by the connection of pipes on a hollow stone. This first derivation has been built in the 6th century [14].

A second derivation occurs approximately 5 m after the first one. Its destination point is not yet known. It is also mainly composed of a canalisation made of the fitting of basic pipes into each other. Just after the beginning of the derivation, a room of visit is observed (point 8 and Fig. 4). The connection between the aqueduct and the room of visit is made of two lead pipes crossing the aqueduct wall, each having a rectangular section of $6 \times 4\ cm^2$. The first pipe of the canalisation is connected to this room. A few meters after the beginning of the derivation, a terracotta decanter was excavated (point 9 and Fig. 5).

These excavations show that the Byzantine city was not only using the Roman aqueduct but was also able to rebuild a new water supply system [14].

The Romans had a remarkable engineering knowledge of water supply [13]. Water was carried to the Roman cities through aqueducts that could reach more than 100 km long. Within the cities, the water was distributed through complex systems of water towers and pipes. Wastewater was evacuated from the cities by drainage systems. Only a few Roman writings on this engineering practice were preserved, but archaeology, as in Apamea, offers some precise illustration of their techniques.

The surviving written records of Frontinus [5,6] and Vitruvius [9] provide some understanding of water supply systems in Roman times. While these works give insight into the design methodology of water supply systems of that period, they reflect pre-scientific views of hydraulic principles [10]. For instance, in the work of Frontinus, a concept such as the flow rate is not known.