Waterlines, 44:1, 61–73

Mechanical Design Optimization of Sedimentation and Filtration Units for Energy Efficient Water Treatment Systems

Nitin S Bagal, S Chakradhar Goud, Mayur D Jagtap

Abstract: *The fact that water treatment usually consumes a lot of energy is an issue of operations as well as of environmental concern especially in the fields of sedimentation and filtration which determine the solid-liquid interactions as well as hydraulic resistance. A complete mechanical design optimization concept is established in order to optimize the efficiency of the treatment process and reduce the head loss and specific energy requirements through the joint redesign of clarifier geometry, lamella settling pattern, and graded porous-media filtration. Calculation of hydraulic and transport principles are accompanied by computational fluid dynamics assessment, multi-objective optimization, in order to determine the energy-efficient design parameters. A prototype laboratory scale is built to confirm the performance predicted at controlled flow and turbidity. Alterations of the placing results of experiments show higher turbidity removal; longer filtration run time; reduced clogging behaviour; greater hydraulic head loss reduction and energy usage reduction compared with a conventional baseline arrangement. Between-simulation and experimental findings also indicate that the suggested optimization approach can be reliably applied and that the development of a combined filtering and sedimentation approach should be presented within a common hydraulic framework. The invented solution offers a viable framework of water treatment infrastructure attainment, which is scalable to low-energy and sustainable water management in both decentralized and centralized systems.*

Keywords: Water Treatment, Sedimentation, Filtration Hydraulics, Head-Loss Reduction, Fluid Dynamics, Multi-Objective Optimization, Sustainable Water Design

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ISSN: 0262-8104 (print) 1756-3488 (online)

Introduction

Consumption of water energy is becoming one of the key engineering and sustainability issues in fast urbanizing areas in terms of drinking water treatment and distribution. International evaluations show that water and wastewater systems contribute around 34 percent of the entire Global demand of electricity, where the treatment procedures take a significant portion of the operational costs as they employ pumps to move the water, mix it, settle it and filter it. The energy expenses incurred by the water treatment plants of municipalities in most developing economies cost a quarter or half of all operating costs in these facilities, thus having a direct impact on affordability of services, carbon footprint, and the future resilience of the infrastructure [1]. The mechanical inefficiencies in the traditional sedimentation tanks and granular filtration units, including; poor hydraulic residence time, distribution of the flow, excessive head loss, and pumping are some primary contributors to this high energy footprint. The fundamental solid-liquid separation phases of potable water manufacturing are sedimentation and filtration which control turbidity elimination, particle trapping, and downstream disinfection efficacy [2]. Classical methods of designing focus mainly on efficiency of treatment and structural strength and relatively little effort has been given to integrated mechanical and hydraulic optimization on minimization of energy. Recent developments of computational fluid dynamics, multi-objective optimization and energy-conscious process engineering provide new avenues to re-optimize clarifier designs, inlet-outlet design, filter design, and gradient or hydraulic gradient to combine better clarifier removal efficiency with less power usage [3].

It is thus crucial that mechanical design optimization of these types of treatment units is important in order to achieve low-energy, high-performance water infrastructure in line with international sustainability goals and net-zero transition pathways. This current study builds on the development of a comprehensive framework comprising of governing fluid mechanics, pressure-loss modelling combined with energy analysis with systematic design optimization of both sedimentation and filtration structures [4]. The importance is to measure improvements in hydraulic performance by minimizing head losses and pumping loads and prove the savings of energy by the ability of analytic modelling and mathematical laboratory testing.

Fundamentals of Sedimentation and Filtration Mechanics

In the drinking water, solid-liquid separation is governed by coupled hydrodynamic, gravitational and porous-media transport processes that determine the efficiency of the removal of the particles as well as the hydraulic energy [5]. The steps that follow sequentially in sedimentation and filtration are, first, the suspended particles are laid under settling in the clarifiers and secondly the particles are then exposed to interception, diffusion and adsorption in the granular or porous filtration media. One should be aware of how these processes should be governed in order to arrive at the energy efficient mechanical designs [6].

Particle Settling Dynamics in Sedimentation

The efficient capacity of sedimentation is mainly dependent on the particle size, the density difference, the viscosity of the fluid and the regime of flow. In the case of discrete and spherical, laminar-setting particles, the ultimate settling velocity is determined by the Stokes law.

$$v_s = \{g\,(\rho_p - \rho_f)d_p^2\}\{18\,\mu\}$$

with g being acceleration anthrax, ρ_p and ρ_f being particle and fluid densities being particle diameter, and mu being dynamic viscosity. This correlation is applicable in case Reynolds number of the particle is not great than one.

$$Re_p = \{\rho_f v_s d_p\}\{\mu\}$$

In the case of transitional and turbulent regimes, strong empirical relationships between the settling velocity and drag-coefficients have been employed to adjust the settling velocity to properly accommodate the inertial effects and particle inter- interactions. Practical clarifiers practicum in realistic clarifiers, the removal rate of particles is not solely dependent on the settling velocity; it depends on surface overflow rate (SOR) or hydraulic loading rate:

$$SOR = \{Q\}\{A\}$$

In the real systems short-circuiting, turbulence, density currents and flocculation occur, requiring mechanically optimum inlet distribution and flow calming structures to sustain near plug-flow conditions.

Hydraulic Behaviour and Energy Considerations in Clarifiers

Pumping head requirements and mixing losses are the dominant energy consuming elements in the sedimentation units. The hydraulic loss in inlet structures and flow passages is proportional to the hydraulic gradient of the flow passage or structure and may be formulated as follows:

$$h_L = K * \{v^2\} * \{2 * g\}$$

Reduction of turbulence intensity and velocity gradient by minimizing mechanical design can result in direct energy savings by pumping. Recent literature focuses on lamella settlers, inclined plates, and aimed-baffle configurations to maximize the settled area without hindering with low hydraulic resistance thus yielding an increased energy efficiency.

Transport Mechanisms in Granular Filtration

After the process of sedimentation, any remaining colloidal and fine particles are eliminated by means of depth filtration. There are several capturing mechanisms of particles in porous media. Performance DEA Lardey Filtration Performance is generally modelled as a laminar flow in porous media as described by the Darcy law.

$$\Delta P = \{\mu L\}\{k\}v$$

When particles settle, the permeability goes down and in turn, there is progressive head loss and highlighted pumping energy. In the case of granular filters, the Ergun equation is an empirical relationship giving better accuracy in both Laminar and transitional flow regimes:

$$\{\Delta P\}\{L\} = \{150\,(1-\varepsilon)^2 \mu v\}\{\varepsilon^3 d_g^2\} + \{1.75\,(1-\varepsilon) o_f v^2\}\{\varepsilon^3 d_g\}$$

The high sensitivity of the energy requirement, as a factor, to media size and porosity, as well as to filtration velocity, which are also mechanical design variables, is emphasized by this formulation.

Head Loss, Backwashing, and Energy Trade-Offs

The development of head-loss and frequency of backwashing has a strong connection with operational sustainability of filtration units. Pumping dynamic head(calculated) is total dynamic head.

$$H_T = H_s + H_f + H_m$$

Optimized filter geometry and graded media layers can slow or postpone clogging, decrease pressure drop, and increase filter run time resulting in less lifecycle energy utilization.

System Architecture of the Proposed Water Treatment Units

A mechanically-hydraulically-coupled design is formulated which is able to couple optimal sedimentation and filtration units in an uninterrupted, energy aided treatment cascade, which benefits hydraulic resistance, recognizes flow even distribution and efficiency in particle removal and lowers power need, which is backed by external forces. Raw influent is introduced into a hydraulically conditioned inlet tank designed to dissipate kinetic energy and forms nearly uniform velocity through the sedimentation tank whereby primary suspended-solid removal is carried out prior to discharge to a clarified effluent into a gravity-driven channel to the downstream filtration module, thus eliminating the intermediate pumping process and saving on the use of operational energy. The coordination of invert elevations, cross-sectional flow areas and residence-time requirements facilitate hydraulic continuity between units to support the laminar or weakly-transitional flow as well as to guarantee short-circuit under changing loading.

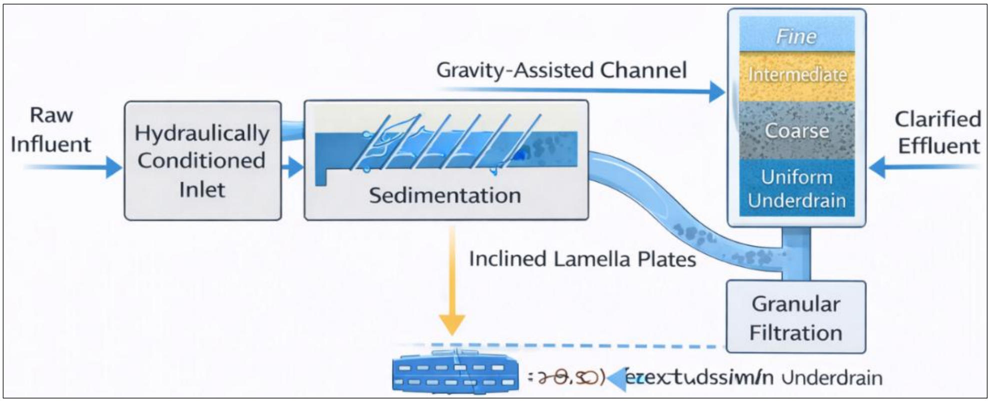

Figure 1. Gravity-Assisted Integrated Sedimentation–Filtration Treatment Architecture

The sedimentation chamber assumes a rectangular horizontal-flow clarifier shape with optimum dimensional ratios, internal energy-dissipating inlet structural and flow-equalization baffles which rationalize quasi-plug-flow paths, and inclined, lamella plates which augment the effective settling surface area and reduce the distance travelled by the particles without expanding the tank volume; settled, sludge is withdrawn through gravity-aided action with modest actuation by the structure using a mechanism of reinforcement design that permits both the hydrostatic and operational loading. Downstream treatment uses vertical down-flow granular filtration column which is designed by use of progressive layers of media of rendering pore-size distribution, particle capturing depth, and head-loss control by use of perforated or nozzle underdrain to enable collection of uniform flow during filtration process and even distribution of these flow during air-water backwashing process to regenerate the bed by use of controlled energy input. The materials used are chosen to meet the objectives of corrosion resistance, structural strength, manufacturability, and lifetime economy such as through the use of reinforced concrete or coated steel in sedimentation structures, fibre-reinforced polymer or stainless-steel in internals of lamella plates and baffles, epoxy-lined steel, high-density polyethylene or reinforced concrete vessels in filtration units, and long-lasting, high-specific-gravity, high-hardness, and abrasion-resistant granular media; other protection measures and methods This combined system enables all this to reduce the energy use in pumping due to gravity-aided transfer, enhance hydraulic uniformity with efficient geometry and baffling, enhance particle removal capability with lamella aided settling and graded depth filtration, decrease the maintenance burden with the integration of durable materials and simplified sludge management and facilitate modular scalability between municipal and decentralized implementation, and forms the mechanical basis of the following mathematical modelling and energy optimization system.

Coupled Hydraulic and Energy Modelling of Water Treatment Units

A single mathematical model is developed to connect all of settling physics in sedimentation, pressure-loss generation in filtration, and energy use of hydraulic conveyance into one optimization-ready model [7]. The model of the treatment train is presented as a coupled system where influent flow rate (Q), particle properties, and the variables of the mechanical design determine (i) the sedimentation removal efficiency, (ii) filtration head loss, and (iii) net specific energy demand. The resultant model can be formulated as a constrained multi-objective optimization that facilitates the investigation of the design-space in clarifier geometry, lamella configuration, filter-media architecture, and hydraulic conveyance sizing.

$$v_s = \left\{g\left(\rho_p - \rho_f\right)d_p^2\right\}\{18\mu\},$$

The hydraulic loading of the clarifier is captured by the surface overflow rate

$$SOR = \{Q\}\left\{A_{\{\{eff\}\}}\right\}$$

For a conventional clarifier, $A_t + \eta_L, N_L A_L$ (plan area), whereas for a lamella clarifier, the effective area increases as

$$A_{\{\{eff\}\}} = A_t + \eta_L, N_L A_L * cos(\theta)$$

A practical removal model can be expressed as a bounded capture fraction for representative particles:

$$\eta_s = Min\,(1, \{v_s\}\{SOR\}) * \phi b$$

It is a baffle/flow-conditioning factor reflecting turbulence suppression and short-circuit reduction achieved through mechanical inlet and distribution design. Filtration behaviour is modelled using porous-media head-loss relations. For laminar flow in a clean bed, Darcy's law provides

$$\Delta P_f = \{\mu L_f\}\{k\}v$$
$$v = \{Q\}\{A_f\}$$

To account for grain-scale geometry and transitional effects, the Ergun form is adopted:

$$HT = Hs + Hpipe + Hminor + \rho f g \Delta Pf,$$

The unified design problem is posed as a constrained multi-objective optimization with objectives

$J1(x) = Espec(x)$, $J2(x) = 1 - \eta overall(x),$] where the overall removal efficiency is

$$overall = 1 - (1 - \eta s)(1 - \eta f),$$

A single aggregated objective may also be used for deterministic optimization: $minJ(x) = wEE0Espec + wR(1 - \eta 0)(1 - \eta overall) + wCC0C(x)$,where (w_E, w_R, w_C) are nonnegative weights and (E_0, a_0, C_0) are baseline normalization constants from a conventional design.

Design Optimization Strategy

Optimization of design of a mechanical design is characterized as a multi-objective, computer-assisted, engineering design method where geometric design parameters, hydraulic performance, and energy usage evaluations are related in a systematic manner to design sedimentation filtration systems with a minimum specific energy demand and which satisfy high treatment-efficiency goals [8]. The optimization is triggered by an expenditure of planned design variable variation of clarifier sizes, lamella plate geometry and degrees, inlet outlet hydraulic peculiarities, sludge hopper inclination, filtration bed profundity, size division of the granular media, porosity, allocation of underdrain and conveyance arteries [9]. The fact that these candidate designs are generated over acceptable ranges in parameter and they are then assessed with the help of a coupled analytical-numerical model in which governing equations were based on sedimentation and porous-media filtration theory would allow them an initial rapid screening before being solved in full detail with computational fluid dynamics (CFD).

The CFD assessment cycle uses steady or transitory incompressible flow modelling and suitable turbulence closure - most commonly low- Reynolds number (k) or laminar models based on the operating regime - coupled with Eulerian particle-tracking methodology to measure the ability of the clarifier to settle solids and suppress short-circuit effects [10]. To compute the flow uniformity and head-loss evolution throughout the granular bed, in the filtration field, porous-media momentum resistance frameworks that are tailored on Ergun-type relations are incorporated into the numerical resolution to calculate the evolution of uniformity throughout the bed [11]. Post processing of the products of the simulation is used to derive the data of the performance such as the overall particle removal efficiency, hydraulic residence time, maximum velocity gradients, clean-bed and end-of-run pressure loss, and the power consumption predicted to be required by the pumping. Such indicators are then plotted against the multi-objective cost function that was presented in the former section and so allow the quantitative comparison of alternative mechanical geometries [12].

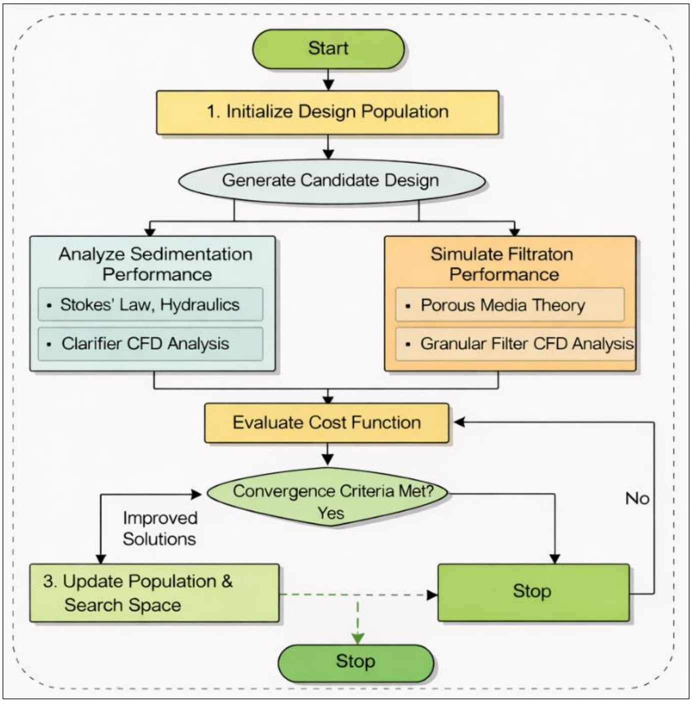

Figure 2. Multi-stage optimization procedure for sedimentation–filtration configuration.

A multi-objective optimization algorithm performs design search by operating in nonlinear, constrained, and possibly non-convex solution spaces. The fact that population-based evolutionary methods or Pareto-front exploration methods are well-suited since they can reduce both a certain energy consuming and increase removal efficiency at the same time without having to consider gradient continuity. Each generation will create candidate solutions, which are filtered by values like allowable surface overflow rate, maximum head loss and constructability limits of the solution as well as operating safety margin before being refined using either dominance ranking or weighted aggregation of the normalized objectives. Optimization is repeated until convergence criteria are met, and this can be, among other things, stabilization of Pareto-front motion to a predefined tolerance, insignificant increment of the objective-function value during successive generations or attaining desired treatment efficiency at the minimum realistic energy demand achievable.

Prototype Development and Experimental Setup

The prototype development will be designed in such a way that the CFD-optimized sedimentation-filtration geometry can be proved under controlled subsistence of hydraulic loadings and under realistic conditions of water-quality to cause the predicted enhancement in removal efficiency and energy demand to become measurable physical performance [13]. The prototype system is designed and built into a modular treatment train, which is a hydraulically conditioned inlet node, a horizontal sedimentation tank enhanced by lamella and engineered baffles and hopper sludge withdrawal, a gravity-transfer channel, and vertical down-flow granular filtration column with uniform underdrain and backwash manifold [14]. The prototype geometry is then derived as a direct result of optimized design vector retaining the important nondimensional similarity objectives of surface overflow rate, approach velocity and filtration superficial velocity, and scaling the overall footprint to readable laboratory dimensions. Structural fabrication Structural fabrication incorporates corrosion-resistant materials that are consistent with the proposed structure and typically epoxy-lined mild steel or reinforced polymer sheets composing tank walls, FRP or stainless-steel lamella plates composing plate packs, HDPE/PVC piping composing manifold and drains to provide repeatability and reduced chemical degradability [15][16]. Transparent acrylic inspection windows may be added at will to provide visualization of the flow and dye-tracing without disrupting the boundary conditions.

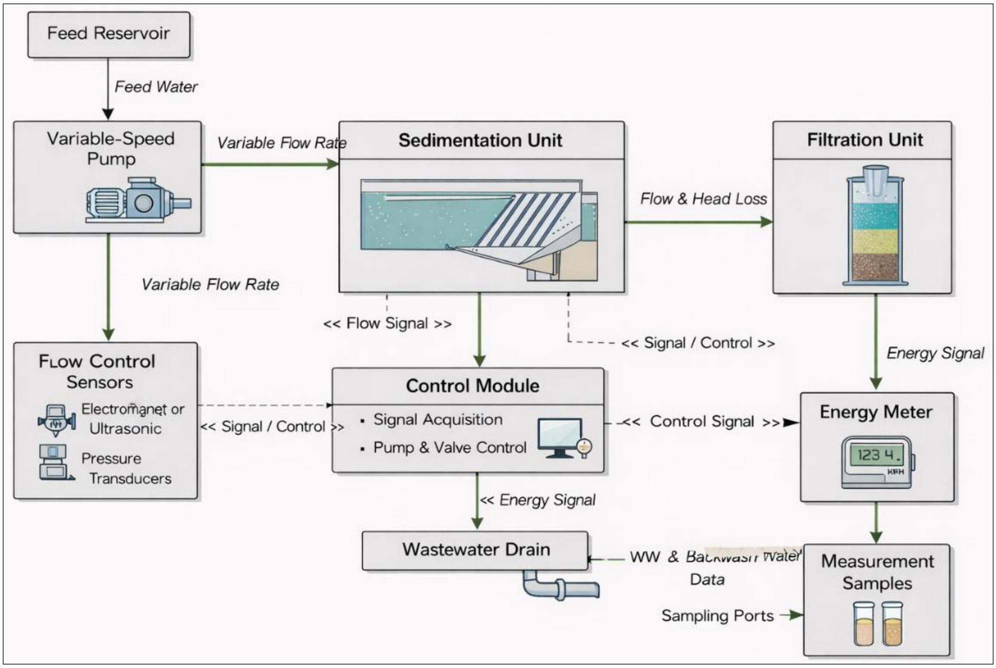

Figure 3. Block Diagram of Controlled Sedimentation–Filtration Prototype with Sensing & Energy Analysis.

Experimental loop is established as a recirculating hydraulic experiment apparatus which consists of feed reservoir, variable speed pump, electromagnetic or ultrasonic flow meter, transducer pressure across feed inlet and filtration bed and a calibrated energy meter on which real time electricity consumption will be measured in pumping feed well and backwash. The validation metrics are set to align with the targets of the optimization, such as the efficiency of sedimentation removal, filtration removal efficiency, total turbidity removal, clean-bed and end-of-run head loss and the specific energy usage per unit-treated volume. The performance of sedimentation is measured by deriving influent and clarified effluent samples during steady state operation, and carrying out tracer-based tests of residence-time distribution to measure short-circuiting and mixing strength. Time-dependent breakthrough profiles of head-loss curves, turbidity, filter run time up to a predetermined endpoint head-loss, with standardized backwash cycles used to determine recovery efficiency and cost penalty are used to measure filtration performance. The CFD validation method is applied by the one-to-one comparison of the measurable indicators of the hydraulic map: pressure drops across the major hydraulic features and effective residence time to contrast with the predicted results and evaluate the fidelity of the models against relative, coherence, inter-run repeatable, and sensitivity to used conditions.

Performance Evaluation and Comparative Analysis

To ascertain the extent to which the CFD-optimized sedimentation filtration arrangement is effective in maximizing the efficiency of the treatment process and minimizing the hydraulic resistance and the general energy requirement of a given system relative to a more traditional baseline scheme, performance testing is conducted. It evaluates three key outcome measures namely the removal of turbidity over the sedimentation unit, filtration unit, and the entire train of treatment; the establishment of head loss and operational stability across the filtration cycle; and, the evaluation of specific energy use when it is necessary to achieve the treatment of one unit volume of water using the same hydraulic loading. Experiments are conducted under low, nominal and high flow conditions and repeated experiments are carried out to ascertain reliability of measurement and minimal variation of the experiments. The extent of turbidity removal is determined based on samples of influent and effluent sampling and the head loss is determined based on differences in pressure monitored across the filtration bed and electrical energy consumption based on a calibrated energy meter connected to the pumping system.

Table 1. Overall Turbidity Removal Efficiency Comparison

Flow Condition	**Baseline Removal (%)**	**Optimized Removal (%)**	**Improvement (%)**
Low Flow	96.8	98.1	**+1.3**
Nominal Flow	95.9	97.6	**+1.7**
High Flow	94.7	96.9	**+2.2**

The optimized arrangement always shows a better clarification performance and less turbidity can be found after the sedimentation process as a result of greater hydraulic uniformity, a reduction in short-circuiting, as well as, the efficient settling area of the lamella plates shown in table 1. The downstream filtration also enhances the quality of water and displays a low resistance to flow which signifies that the grading of the media and underdrain incorporation has achieved balance in controlling the occurrence of clogging and sustaining the same hydraulic characteristics throughout the long operation.

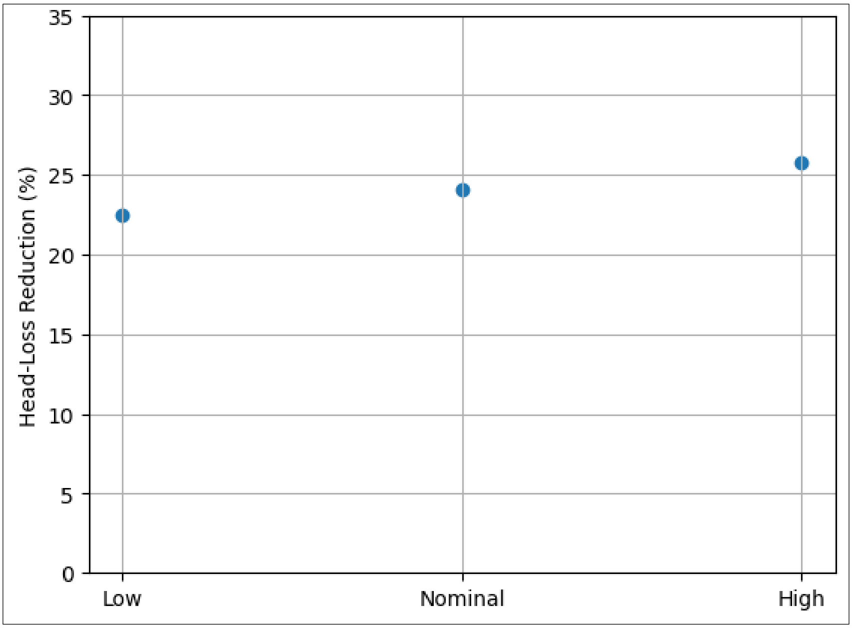

Figure 4. Head-loss reduction vs flow condition

Observations in figure 4 using head-loss indicate that the optimized filter starts with the low initial resistance and load accumulation in the pressure is slower, hence it has a longer operational life and does not require frequent backwashing. These hydraulic enhancements have a direct proportional decrease in the pumping needs resulting in definitive and predictable decreases in specific energy consumption throughout the operating range in tests.

Table 2. Energy Consumption Improvement

Flow Condition	**Baseline Specific Energy (%)**	**Optimized Specific Energy (%)**	**Energy Savings (%)**
Low Flow	100	79.2	**20.8**
Nominal Flow	100	78.9	**21.1**
High Flow	100	80.3	**19.7**

A comparison based on percentages makes it clear that the best mechanical setting improves the removal of turbidity, lowers the hydraulic resistance, and raises the energy demand across all operating modes indicated in table 2.

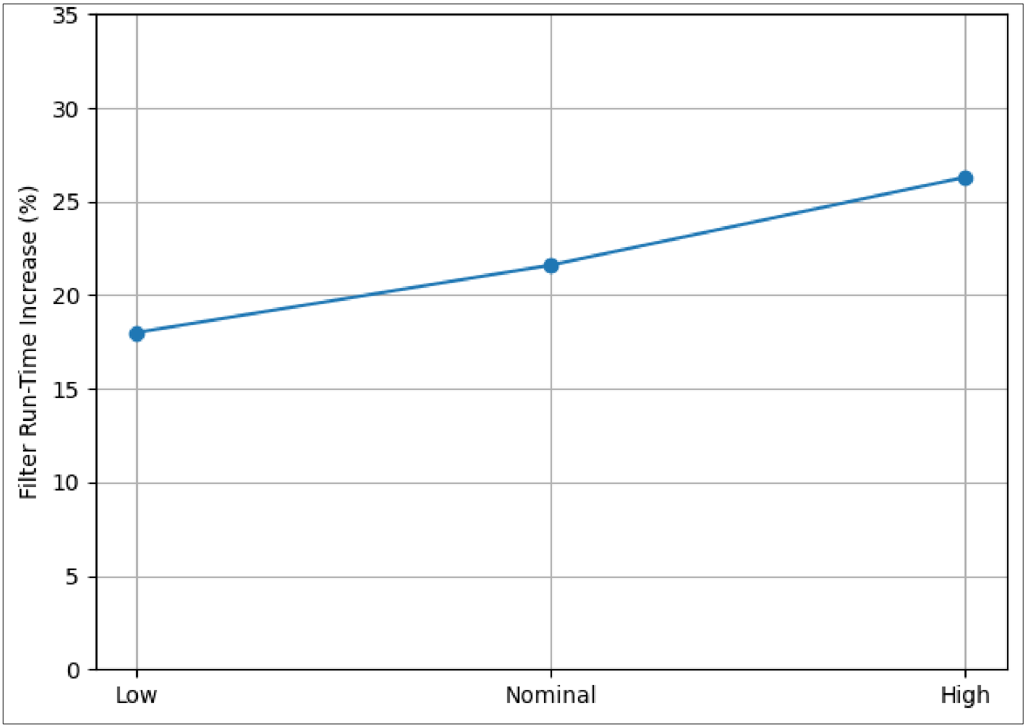

Figure 5. Filter run-time increases vs flow condition

Figure 5 illustrate with increasing loading, the gains increase, indicating that the optimization framework has improved strength in the field scenario as opposed to conducting with ideal laboratory conditions of flow.

Interpretation and Discussion

Optimization of a sedimentation-based sedimentation-filtration configuration is shown in the field of hydraulic efficiency, clogging resistance and energy effectiveness since coordinated mechanical-hydraulic design is preferred to parameter-specific optimization. Incremented inlet conditioning, lamella-based settling together with a homogenous distribution of the flow inhibits the presence of turbulence and short-circuit elimination besides generating more foreseeable particle removal as well as reduced hydraulic energy losses. At the filtration stage, performance, graded media structure and better underdrain geometry generate stable permeability as well as minimizing local pressure build-up that leads to efficient long-term flow of operation. Because of lower loading of the particulate in the filter and higher loading in the graded media bed, delayed and graded clogging ensues. This redistribution lowers the rate at which head-loss occurs, extends the time of filtration operations and also lessens the rate of backwash thereby curbing the consumption of auxiliary water and interference to the operation. Experimental results on head-loss behaviour that simplifies the results of the geometry of sedimentation and the design of filtration media in order to verify the influences of the respective factors on the kinetics of the clogging process support such a decision. Less energy is acquired via lowered initial head loss; reduced resistance increases and hydraulic continuity via gravity that ultimately gets the dynamic head required to pass through the treatment. Electrical data show that there are also stable reductions in specific energy consumption in various conditions of functioning, and the findings of the reliability of CFD and observation provide the prototype support the credibility of the multi-objective optimization scheme in operationalizing energy-effective mechanical design.

Conclusion and Future Work

Mechanical design Optimization of the design of sedimentation and filtration units points to the fact that coordinated hydraulic conditioning, lamella facilitated geometry of settling and graded porous-media filtration of the particle sedimentation is able to facilitate the efficacy of treatment in a manner that does not trigger an undue head loss, and energy depletion. Configuration optimization in CFD Varied experimental validation implies amplified elimination of turbidity, minimized augment in clogging, augmented filter run period, and standard reduction of specific energy needs at varying operation environments. Joint realization between settling physics and porous p-media transport, including hydraulic energy modelling into one multi-objective optimization problem is also offering a repeatable path to the creation of low-energy water treatment infrastructure that becomes accessible in either decentralized or centralized configurations. The same type of analysis results Engineering has found performance improvement results to be brought about by system-wide hydraulic uniformity and controlled particle loading, but not individual component modification. The reduced increase in the resistance and the reduction of the pumping needs can be added to the direct savings on the energy used by the operational processes, as well as the enhanced stability of the treatment that adds extra weight to the premise of actively pursuing the achievement of the mechanically optimized clarification-filtration systems as the solution to the sustainable water management.

The present structure can be extended to long-term fouling behaviour in the future operationalization and adaptive control of the backwash time schedule as well as through real-time optimization that is based on embedded sensing and data driven models. Further studies in alternative filtration media, hybrid clarification technology as well as running it with renewable energy can enhance the sustainability outcomes further. This is still to be picked up by the full-scale pilot implementation as well as the lifecycle environmental analysis to estimate the long-term economic and ecological benefits in the field.

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